

<PROJECT NUMBER>

FINDING THE BALANCE BETWEEN WASTEWATER TREATMENT NUTRIENT REMOVAL AND SUSTAINABILITY, CONSIDERING CAPITAL AND OPERATING COSTS, ENERGY, AIR AND WATER QUALITY, AND MORE

Michael W. Falk, PhD
HDR Engineering

David J. Reardon, BCEE, PE
HDR Engineering

JB Neethling, PhD, PE
HDR Engineering

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For more information, contact:

Water Environment Research Foundation
635 Slaters Lane, Suite 300
Alexandria, VA 22314-1177
Tel: (703) 684-2470 Fax: (703) 299-0742
www.werf.org werf@werf.org

This report was co-published by the following organizations. For nonsubscriber sales information, contact:

Water Environment Federation
601 Wythe Street
Alexandria, VA 22314-1994
Tel: (800) 666-0206
Tel: (703) 684-2452
Fax: (703) 684-2492
www.wef.org
pubs@wef.org

IWA Publishing
Alliance House, 12 Caxton Street
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Fax: +44 (0) 20 7654 5555
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publications@iwap.co.uk

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Report Preparation

Principal Investigator:

David J. Reardon, MS, BCEE, PE
HDR Engineering

JB Neethling, PhD, PE
HDR Engineering

Project Team:

Michael W. Falk, PhD
HDR Engineering

Place Names in Alphabetical Order

Project Subcommittee

<Full Names and Degrees of All PSC Members>

<Organizations of Project Subcommittee Members>

Place Names in Alphabetical Order

Water Environment Research Foundation Staff

Director of Research: Dr. Amit Pramanik

Project Manager: <Full Name and Degree>

ABSTRACT AND BENEFITS

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EXECUTIVE SUMMARY

ES.1 Background and Goals

The USEPA has noted that high nitrogen and phosphorus loadings result in harmful algal blooms reduced spawning grounds and nursery habitats, fish kills, oxygen-starved hypoxic or “dead” zones, public health concerns related to impaired drinking water sources, and increased exposure to toxic microbes (USEPA, 2010). The most widely known examples of significant nutrient impacts include the Gulf of Mexico and the Chesapeake Bay.

Four watersheds of particular importance to EPA include:

- ☐ Chesapeake Bay has an existing hypoxia problem and adds 150,000 new people a year to the watershed.
- ☐ The Gulf of Mexico has a prevalent and well-documented hypoxic “dead” zone. Thirty-one states contribute to the watershed and, through the 2001 Hypoxia Action Plan, the EPA Science Advisory Board reports that phosphorus plays a much greater role in the hypoxia problem than previously thought.
- ☐ In the Long Island Sound, DO is below standards in one-third to one-half of the Sound. Nitrogen loadings have been capped at 1990 loads, and a water quality trading program has been implemented in Connecticut for point sources with a market-based approach.
- ☐ In Puget Sound, the highest priority is to gain a better understanding of nutrient and bacteria loadings from septic systems through the Puget Sound Action Plan.

The USEPA’s approach towards issuing nutrient discharge limits is based on site-specific standards. Other government agencies and grassroots’ organizations contend that nutrient pollution is widespread and justifies a general standard. In particular, the Natural Resources Defense Council (NRDC) has actively pursued the EPA towards a quantified nutrient pollution discharge limit for wastewater treatment facilities. The Sierra Club, American Rivers, and others have joined NRDC in their pursuit. NRDC argues that the USEPA must establish nutrient limits as a means to protect the general public. The NRDC recommends the following effluent nutrient levels:

- ☐ Effluent TP 0.3 mg/l and TN 3 mg/l are Consistently Attainable Using Current Technology
- ☐ Effluent TP 0.5 mg/l and TN 5 mg/l are Consistently Attainable Using Current Technology
- ☐ Effluent TP 1 mg/l and TN 8.0 mg/l is Attainable with Existing Technology Using Only Improved Biological Treatment Processes

The discussion to restrict nutrient discharges, namely nitrogen and phosphorus, has largely focused on receiving water quality and ignored the corresponding impact on sustainability from treatment. This report was prepared to provide a bench-top analysis on the balance between nutrient removal and sustainability. The objective is to determine if a point of “diminishing returns” is reached where the sustainability impacts of increased levels of nutrient removal outweigh the benefits of improved water quality. The measurement used to quantitate the environmental impacts is greenhouse gas (GHG) emissions since it provides a means to normalize data for comparative purposes. Given that sustainability is a broad term, the focus was placed on the following variables while developing the comparative model:

- ☐ GHG Emissions
- ☐ Capital Costs
- ☐ Operating Costs
- ☐ Energy Demand
- ☐ Air and Water Quality
- ☐ Consumables, such as chemicals, gas, diesel, etc.

ES.2 Five Levels of Treatment

The analysis considered the sustainability impacts of treatment plants designed to achieve five different levels of nutrient removal as shown in Table ES - 1. With each treatment level, a process analysis was developed to quantitatively determine the GHG emission equivalents based on the aforementioned parameters. The treatment process trains are outlined in Table ES - 2.

Table ES - 1. Treatment Level Objectives

Level	Biochemical Oxygen Demand (mg/L)	Total Suspended Solids (mg/L)	Total Nitrogen as Nitrogen (mg/L)	Total Phosphorus as Phosphorus (mg/L)
0	30	30	<30	<30
1	-	-	8	1
2	-	-	4-8	0.1-0.3
3	-	-	3	<0.1
4	-	-	1	<0.01

Table ES - 2. Unit Processes per Treatment Level

Level	Liquid Treatment	Solids Treatment	Comment
0	Primary Clar. Act. Sludge Disinfection Dechlorination	Gravity Belt Thickener Anaer. Digestion with Cogen Centrifugation	Conventional Activated Sludge for BOD/TSS removal
1	Primary Clar. Act. Sludge Alum (optional) Disinfection Dechlorination	Gravity Belt Thickener Anaer. Digestion with Cogen Centrifugation	Nitrification/Denitrification with MLE
2	Primary Clar. Act. Sludge Methanol (optional) Alum (filtration) Filtration Disinfection Dechlorination	Gravity Belt Thickener Anaer. Digestion with Cogen Centrifugation	Nitrification/Denitrification with MLE and filtration
3	Primary Clar. Act. Sludge Methanol (optional) Alum/Polymer (Enhanced Settling) Enhanced Settling Filtration Disinfection Dechlorination	Fermentation Gravity Belt Thickener Anaer. Digestion with Cogen Centrifugation	Nitrification/Denitrification with MLE, high rate clarification and denitrification filter
4	Primary Clar. Act. Sludge Methanol (optional) Alum (filtration) Filtration Micro-filtration Reverse Osmosis Disinfection Dechlorination	Gravity Belt Thickener Anaer. Digestion with Cogen Centrifugation	Nitrification/Denitrification with MLE, high rate clarification, denitrification filter, and side- stream RO

ES.3 Results

The investigation determined that as the degree of nutrient removal increased, the impact on sustainability (as measured by green house gas) increased significantly. Results are presented in Table ES - 3 and Figure ES - 1. For the purpose of consistency, all plants were evaluated at a nominal flow of 10 mgd. Note that the negative GHG values represent the benefit of cogeneration (resulting in a reduced amount of electricity purchased), which is assumed for all levels of treatment. The amount of GHGs roughly doubles as the treatment objective increases from Levels 0 to 1, 2 and 3. However, achieving treatment Level 4 (N=1 and P<0.01) resulted in a dramatic additional increase, doubling of GHGs over treatment Level 3 alone. This sharp increase suggests that a point of diminishing returns may be reached since a small improvement in water quality caused a very large impact on the overall environment.

Table ES - 3. Greenhouse Gas Emission Results for Five Levels of Nutrient Treatment (10 mgd)

Treatment	Level 0 No N/P Removal	Level 1 8 mg/L N 1 mg/L P	Level 2 4-8 mg/L N 0.1-0.3 mg/L P	Level 3 3 mg/L N <0.1 mg/L P	Level 4 1 mg/L N <0.01 mg/L P
	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)
Sub-Total Pri.	238	238	238	238	238
Sub-Total Act. Sludge	1,471	2,605	2,844	2,836	2,836
Sub-Total Tertiary	203	487	652	1,354	6,826
Sub-Total Liquid Stream	1,913	3,331	3,735	4,428	9,900
Sub-Total Solids	-294	-56	-91	19	19
Total	1,619	3,274	3,643	4,447	9,919

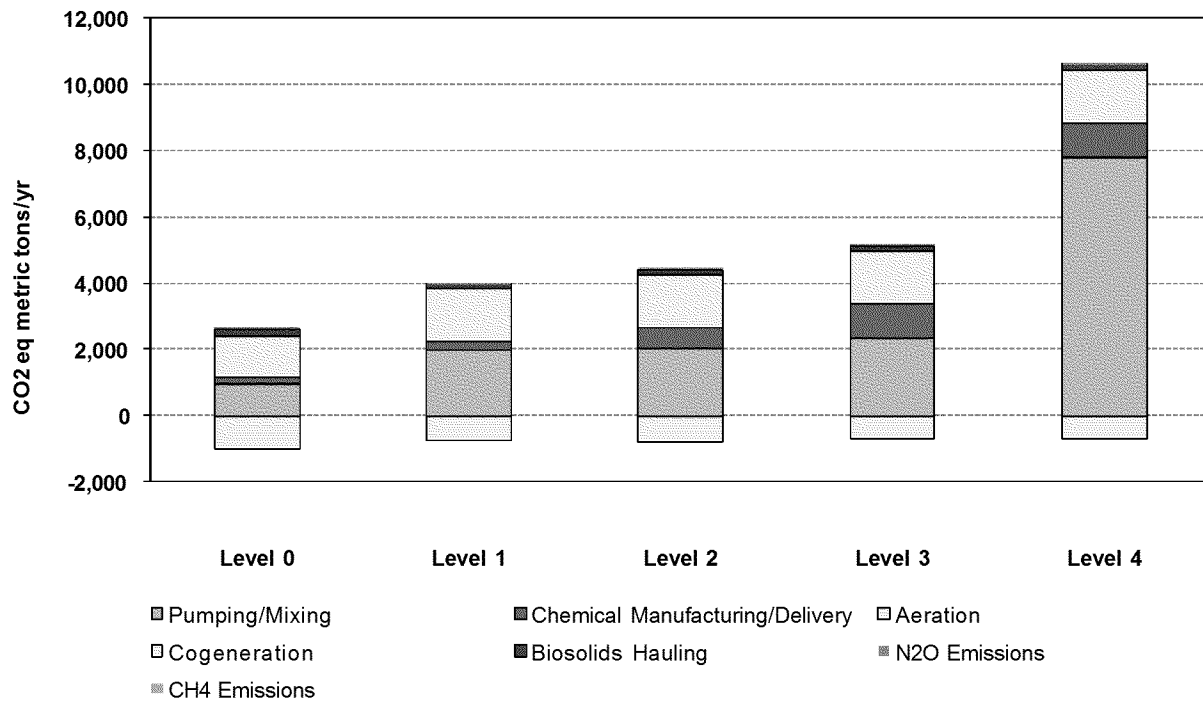


Figure ES - 1. Combined Liquid and Solids Stream Mass Balance GHG Results (10 mgd)

While the above results seem dramatic, they are further magnified when the GHG impacts are expressed in terms of the incremental amount of N and P removed by each level of treatment, respectively. As shown in Figure ES - 2 and Figure ES - 3, unit increases in GHG per level of pound of nitrogen or phosphorus removed increases sharply for all treatment beyond Level 2, increasing by an order of magnitude and more. Note that these graphs are on logarithmic scale. These figures indicate that the GHG impact on the incremental removal (the last pound removed) is significantly higher than the initial benefit.

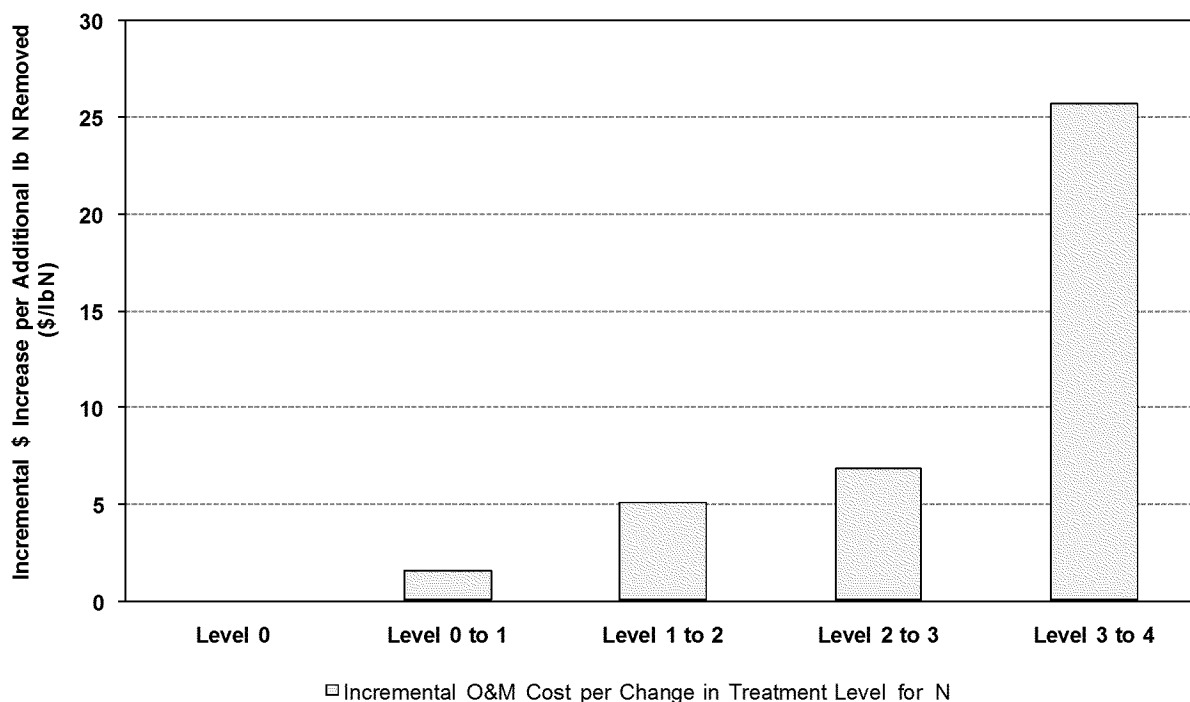


Figure ES - 2. Incremental GHG Increase per Additional lb N Removed (Note: y axis is on logarithmic scale)

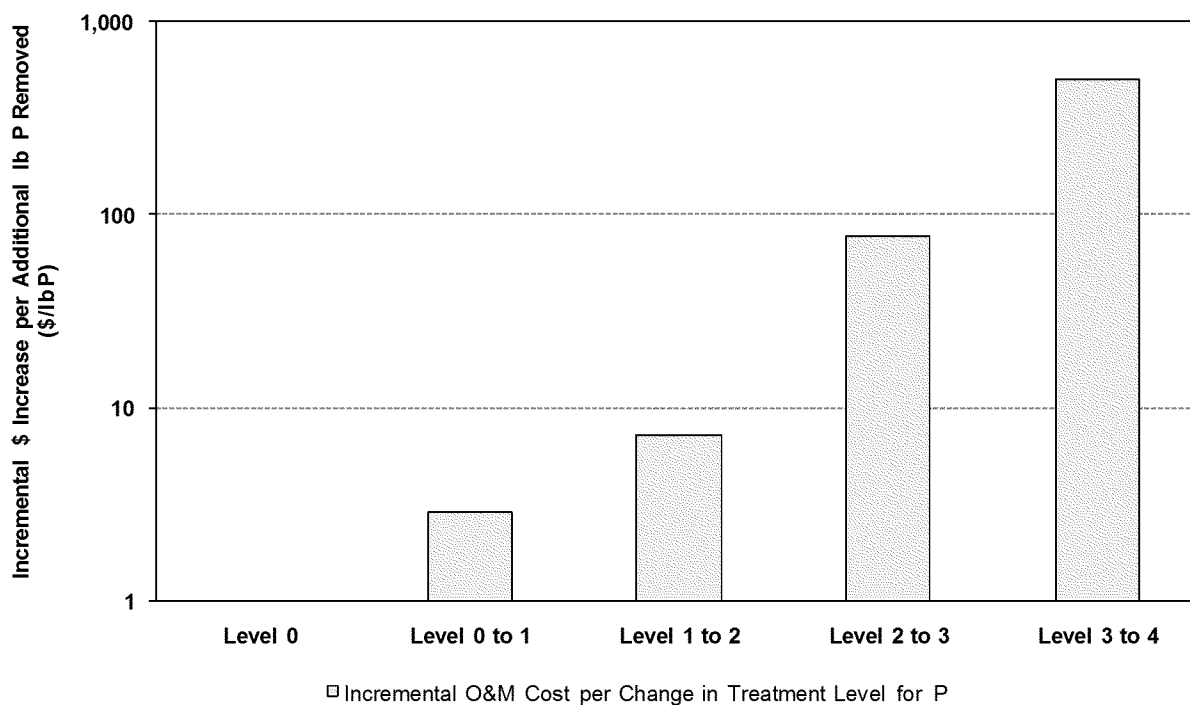


Figure ES - 3. Incremental GHG Increase per Additional lb P Removed (Note: y axis is on logarithmic scale)

Operational sustainability impacts (as measured by GHG) are not the only impact of increasingly restrictive nutrient limits. The impacts of the treatment levels on construction costs

are shown in Table ES-4. Increased treatment levels can nearly triple the capital cost of treatment compared to conventional secondary treatment. The impact on operational cost is even more pronounced as a direct result of increased aeration demand, pumping, mixing, chemicals, and others required to achieve the more stringent levels. It is important to note that the operations cost do not include labor or maintenance.

Table ES - 4. Capital and Operations Costs for Each Treatment Level

Level	Capital Costs (\$/gpd)	Capital Costs for 10 mgd (Million \$)	Operations Cost (\$/MG Treated) *	Operations Cost (\$1,000/yr/10 MG Treated) *
0 (No N/P Removal)	7.3	73	191	696
1 (8 mg/L N; 1 mg/L P)	12.5	125	335	1,222
2 (4-8 mg/L N; 0.1-0.3 mg/L P)	13.3	133	510	1,861
3 (3 mg/L N; <0.1 mg/L P)	13.8	138	690	2,517
4 (1 mg/L N; <0.01 mg/L P)	20.0	200	1,183	4,319 **

Notes:

* Includes pumping, mixing, aeration, and chemicals. Does not include labor cost.

** Does not include membrane replacement costs as this is highly dependent on membrane material and operating conditions. MF/RO replacement costs estimated to be \$240,000/yr for a 10-yr life-span

In summary, increased levels of treatment for nutrients substantially impacts sustainability of WWTPs as expressed in GHG emissions and costs. The GHG production and capital costs for high levels of nutrient removal increase rapidly with increased nutrient removal. The impact/benefits ratio (GHG emission per lb nutrient removed) increases rapidly as the treatment level increases since the mass of nutrients eliminated is reduced and the cost increases. A rational methodology is required to assess the cost and GHG impacts of point source nutrient removal benefit of reduced nutrients on the water quality.

ES.4 Future Work

1. In many regions of the country, non point sources contribute higher nutrient loads than point sources. A rational approach to receiving water nutrient loading such as implementing “best practices” for non point sources may be much more practical than requiring WWTPs to remove nutrients to levels that adversely impact sustainability. Further dialog with regulators on a national and local level is needed to find a regulatory framework that best protects water quality and manages GHG emissions using both non point and point source control
2. Clearly define whether N or P is the limiting nutrient for specific receiving waters.
3. A discussion needs to be initiated with the EPA regarding making N and P limits only on bioavailable N and P; thus taking a portion of rDON and rDOP out of the equation.
4. Initiate research on membranes that discriminate between rDON/rDOP and mono- and divalent ions as a means to overcome brine management issues related to Level 4 (reverse osmosis).

ES.5 Conclusions

1. Removing N and P using treatment Levels 3 and 4 may result in negative sustainability impacts that far outweigh the potential improvements to water quality.
2. Removing nutrients results in significant impacts on WWTP sustainability as measured by GHG emissions. For a nominal 10 mgd WWTP, the GHG emissions increased from 1620 CO₂ equivalent metric tons per year for a conventional secondary plant (Level 0 treatment) to 4,450 CO₂ equivalent metric tons per year where nitrogen and phosphorus removal requirements are 3 mg/l N and <0.1mg/l P (Level 3 treatment). Further reductions in N and P to 1 mg/l and 0.01 mg/L (Level 4 treatment) increase the GHG emissions to 9,920 CO₂ equivalent metric tons per year.
3. Nutrient removal also increases the capital cost and operating costs of WWTPs. Capital cost increased from \$73 million for a Level 0 facility to \$138 million for a Level 3 facility and \$200 million for a Level 4 facility. Operating costs for a level 0 facility are \$696,000 per year and \$4.3 million per year for a level 4 facility.
4. The GHG nutrient removal intensity (GHG per incremental pound of N and P removed) increases geometrically as the level of treatment increases. The intensity for moving from level 0 to level 1 is 1.6 for N and 2.9 for P. The intensity for moving from level 3 to level 4 is 26 for N and 504 for P.
5. Recalcitrant dissolved organic nitrogen, commonly referred to as refractory dissolved organic nitrogen (rDON), impairs municipalities ability to reliably achieve low TN objectives. Effluent limits that require nitrogen values of 2 mg/l or less might require the use of expensive and energy intensive strategies, such as reverse osmosis, that result in monumental GHG emissions.
6. As with rDON, Recalcitrant dissolved organic phosphorus, commonly referred to as rDOP, hinders a municipalities to meet the total phosphorus value required of Level 4. As a result, an energy intensive technology, such as RO, is required to ensure reliably meeting the treatment objective.
7. The GHG impacts of all levels of treatment in this document are dominated by energy demand.
8. Based on the incremental GHG increase per incremental removal, a point of diminishing returns is reached between Level 2 to 3 for both nitrogen and phosphorus removal.
9. Using reverse osmosis to achieve extremely low levels of nitrogen and phosphorus is impractical due to high costs, significant impacts on GHG, and brine disposal challenges.

CHAPTER 1.0 - OVERVIEW

Regulatory trends imposed by Federal and State Agencies suggest that many wastewater treatment plants (WWTPs) may be required to remove ammonia, nitrogen, and/or phosphorus from their discharge over the next several years. In many instances, the required effluent nutrient concentrations are very low, approaching the best performance achievable with current technologies. This white paper focuses on the sustainability impacts as WWTPs implement treatment technologies to meet nutrient limits.

This white paper provides an analysis on striking a balance between nutrient removal and sustainability. The objective is to determine if a point of “diminishing returns” is reached where the sustainability impacts of increased levels of nutrient removal outweigh the benefits of a better water quality. The measurement used to quantify the sustainability impacts is greenhouse gas (GHG) emissions since it provides a means to normalize data for comparative purposes. Given that sustainability is a broad term, the focus was placed on the following components while developing a comparative model for five varying nutrient discharge limits:

- ☐ GHG Emissions
- ☐ Capital Costs
- ☐ Operating Costs
- ☐ Energy Demand
- ☐ Air and Water Quality
- ☐ Consumables, such as chemicals, gas, diesel, etc.

The comparison considered the requirements and impacts of a treatment plants designed to achieve five varying levels of nutrient removal as shown in Table 1. With each treatment level, a process analysis was developed to determine the GHG emission equivalents based on the aforementioned parameters.

Table 1. Treatment Level Objectives

Level	Biochemical Oxygen Demand (mg/L)	Total Suspended Solids (mg/L)	Total Nitrogen as Nitrogen (mg/L)	Total Phosphorus as Phosphorus (mg/L)
0	30	30	-	-
1	-	-	8	1
2	-	-	4-8	0.1-0.3
3	-	-	3	<0.1
4	-	-	1	<0.01

The overall findings revealed that from a sustainability perspective (i.e., GHGs), a point of diminishing return is reached from a sustainability perspective after the Level 3 treatment objective. Level 4 requires exceptional higher operational and energy expenses, as well as chemicals that have a significant impact on the GHG emission equivalents.

CHAPTER 2.0 – WASTEWATER TREATMENT PLANTS IMPACT ON SUSTAINABILITY

2.1 Sustainability

Sustainability means different things to different people. Ask 100 people for a definition and you will get 100 different answers. The classic definition of sustainability was created by the Brundtland Commission, formally the World Commission on Environment and Development (1987):

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

This general description serves as a starting point. However, quantifiable metrics are needed to determine and assess the environmental impacts. Considerable attention has been focused on greenhouse gases (GHGs) as a contributor to climate change over the last century. Greenhouse gas evaluations often concentrate on fossil fuels combustion. The sustainability impacts of WWTPs must also include chemical consumption, production of nitrous oxides and methane (both potent greenhouse gases), biosolids haul/reuse, and emissions (particularly of methane) created in the wastewater collection system. Some of these items are difficult to measure and only limited data exists for many contributions such as fugitive methane escaping the plant, nitrous oxide production in the activated sludge basins, and methane entering the plant with raw sewage.

For this investigation, we will focus on GHG as the metric for sustainability. This is a simplified approach than facilities consistent methodology for measurement without investigating the array of economic, social and environmental sustainability impacts that are difficult to quantify.

2.2 Role of Wastewater Treatment Plants in Sustainability

A nationwide breakdown found ‘waste’ to represent 2.3 percent of the estimated US GHG emissions (EPA, 2007). ‘Waste’ in this case entails landfills, wastewater treatment, and composting. Of those, landfills represent over 75 percent of the 2.3 percent and wastewater treatment plants at less than 1 percent. Despite representing a small amount of national GHG emissions (<1 percent), GHG savings audits for municipalities that reduce energy demand can

represent significant GHG emission savings opportunities on a local level. For example, Wett and others (2007) have shown that WWTPs can be designed to achieve zero net energy demand under certain conditions. The facility in Strass, Austria, where Wett and his colleagues performed their research, had a permit (14 mg/L total nitrogen as nitrogen) that lends itself towards carbon neutral operation. As the nitrogen discharge requirement drops below 14 mg/L as nitrogen, the energy demand increases to a level where carbon neutral is more difficult to achieve. Given that the nitrogen removal levels considered in this paper are all less than 14 mg/L as nitrogen, achieving carbon neutral energy usage is highly unlikely.

2.3 Previous GHG Emission Results

This white paper addresses the relationship between greenhouse gas (GHG) emissions and effluent discharge targets. Despite several studies that have quantified GHG emissions per treated wastewater (Keller and Hartley, 2002; Monteith et al., 2008; de Haas and Hartley, 2004), no study to our knowledge has considered the impact of stringent total nitrogen (TN) and total phosphorus (TP) limits on GHG emissions. Quantifying the amount of GHG emissions per gallon of treated wastewater for a wide range of nutrient discharge limits will provide insight into whether or not a point of diminishing returns is reached with respect to nutrient effluent targets and sustainability impacts in the form of GHG emissions.

A literature review of the existing knowledge on sustainability at WWTPs and how it relates to nutrient removal target objectives is discussed below with an emphasis on the following:

- Previous GHG results from WWTPs
- The importance of establishing boundary conditions
- Impact of nutrient removal on WWTPs sustainability by way of GHG emissions

A summary of previous studies that have quantified GHG emissions from various WWTPs is provided in Table 2. The results range from 1,700 to 10,000 CO₂ equivalent metric tons per year, for the referenced studies scaled to a 10 mgd influent flow. The wide range in values is based on the lack of defined boundary conditions used for each study.

Table 2. Other GHG Emission Results with Values Scaled to 10 mgd Influent Flow

Source	CO ₂ equivalents (metric tons CO ₂ /yr)	Treatment Configuration
de Haas and Hartley, 2004	5,300 – 7,400	BNR Facility (w/Anaerobic Digestion and Energy Recovery)
Wallis-Lage et al., 2009	1,700	BNR Facility (w/Anaerobic Digestion and Energy Recovery)
Tripathi, 2007 ⁱ	7,200	Conv. Act. Sludge Tertiary Filtration No Digestion
Tripathi, 2007 ⁱⁱ	8,000	BNR Facility (w/Anaerobic Digestion and Energy Recovery)
Tripathi, 2007 ⁱⁱⁱ	10,000	BNR Facility

Source	CO ₂ equivalents (metric tons CO ₂ /yr)	Treatment Configuration
		(w/Anaerobic Digestion and Energy Recovery)
HDR Engineering (Easterly WWTP, Vacaville, CA)	5,000	Nitrogen Removal Tert. Filtration 6 months/yr (w/Anaerobic Digestion and Energy Recovery)
Keller and Hartley, 2003	7,800	Conventional Act. Sludge (w/Anaerobic Digestion)

Notes:

- i Ann Arbor WWTP
- ii Laguna WWTP
- iii Ypsilanti Community Utilities Authority

2.4 System Inputs

The extents of calculated GHG emissions at wastewater treatment plants (WWTPs) are highly variable as shown in Table 2. The variability is in part due to the lack of consensus on system inputs. For example, the energy production to operate the WWTP is not always incorporated into the GHG emissions. Additionally, the GHGs associated with manufacturing and distributing the chemicals used for treatment is not necessarily included in ones GHG emissions calculations. The existing non-uniform approach complicates the issue while attempting to compare studies.

The Climate Registry's (2008) proposed a means to define emissions boundary conditions by placing them into three different "scopes" labeled 1, 2, or 3 emissions. The criteria for those 3 emissions groupings are outlined below:

- **Scope 1 – Direct on-site GHG emissions. These are generally described as anthropogenic GHG (those related to man's activities):**
 - On site production of electricity, heat or steam using fossil fuels
 - Physical or chemical processing
 - Transportation of materials, products, waste, and employees
 - Fugitive emissions
 - Natural gas combustion

For WWTPs, key Scope 1 emissions are presented in Table 3.

Table 3. Scope 1 - Direct GHG Emissions from Wastewater Treatment Processes

WWTP Process	Scope 1 - GHG Emission
Primary Treatment	None Expected. Fugitive CH ₄ (considered minimal)
Secondary Treatment	None expected from well managed aerobic/trickling filter process operating in carbonaceous BOD removal mode
Nutrient Removal	N ₂ O from nitrification-denitrification biological processes
Advanced Treatment	CO ₂ emissions associated with physical/chemical processing by filtration/membranes
Solids Handling	CH ₄ from incomplete combustion of digester gas Fugitive CH ₄ (considered minimal)

WWTP Process	Scope 1 - GHG Emission
Fugitive Emissions	Intentional/unintentional releases of GHGs from joints, seals, gaskets, etc. (e.g. methane leaks from digesters)
Heat/Power generation	Natural gas combustion or fossil fuel used for use in boilers, prime movers, HVAC units, and power generation

Carbon dioxide produced in the biological treatment processes and from cogeneration from biogas is considered biogenic and thus, not included as Scope 1 emissions. Biogenic carbon is part of the natural carbon balance and it will not add to atmospheric concentrations of carbon dioxide (IPCC, 2006).

☐ **Scope 2 – Indirect GHG emissions from imports (or purchases) of electricity, heat, or steam.**

For most WWTPs, this is dominated by purchased electricity

☐ **Scope 3 – Other Indirect Supply-Chain GHG emissions. These GHG emissions sources are consequences of the activities of the reporting entity, but occur from sources owned or controlled by another entity:**

- ☐ Transportation of products, materials, and waste
- ☐ Outsourced activities
- ☐ Emissions from waste
- ☐ Emissions from final product disposal
- ☐ Employee commuting
- ☐ Production of imported materials, such as chemicals

For WWTPs, the dominant scope 3 focal areas are biosolids hauling/reuse, waste hauling, chemical manufacturing and hauling, and employee commuting.

2.5 Future Regulations

The EPA set out in 1998 to set numeric nutrient criteria in all states. The EPA's goal at the time was to implement nutrient numeric standards in all states by 2002. Although currently unsuccessful at meeting this goal, Some States have made notable progress since the EPA's inception of their goal. It is anticipated that the EPA's vision of a quantitative nutrient discharge standard will be put into action over the next several years. A detailed discussion on the regulatory outlook can be found in Chapter 4 - Regulations and Driving Forces.

2.6 Impact of Nutrient Removal on GHGs at WWTPs

This sub-section will provide a background on the fundamentals of nutrient removal in WWTPs. The background is followed by a brief overview on the difficulty in meeting stringent nutrient removal discharge values per nutrient. It is important for the reader to understand the

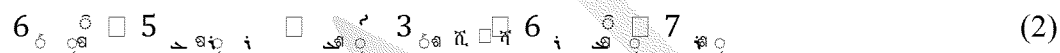
difficulty that municipalities face in meeting the more stringent nutrient removal permits, such as Level 4 (TN = 0.1 mg/L as N, TP = 0.01 mg/L as P). Once the nutrient removal framework is established, this knowledge is complemented with a discussion on greenhouse gas emissions at WWTPs and how the two are connected with each other. For example, meeting the most stringent nutrient removal criteria in Level 4 (TN = 0.1 mg/L as N, TP = 0.01 mg/L as P) requires reverse osmosis (RO). The brine reject of RO requires an energy intensive brine management solution, such as deep well injection, that more than doubles the overall GHGs for the municipality.

2.6.1 Nutrient Removal

The removal of nitrogen from wastewater treatment plants (WWTPs) is primarily achieved by (a) assimilation of nitrogen into biomass and (b) biochemical oxidation/reduction processes that convert organic nitrogen and ammonia to nitrogen gas through a two-step process. The two-step process is commonly referred to as nitrification and denitrification, whereby nitrification entails the oxidation of ammonia to nitrate by nitrifying organisms:



followed with denitrification by denitrifying bacteria that utilize organic carbon as electron donor to reduce nitrate to nitrogen gas:



Many different combined nitrification and denitrification configurations are employed in secondary wastewater treatment plants to reduce nitrogen effluent discharge levels to 4 - 8 mg/L TN. A more detailed discussion on nitrification/denitrification, as well as the various secondary treatment configurations can be found in MOP-8 (WEF, 2009).

Inorganic oxidation of ammonia to nitrogen gas using nitrite is used to treat high strength wastewater using the anammox bacteria. This process is emerging as an attractive option for treating dewatering return streams.

The other nutrient of interest, phosphorus, can be removed from WWTPs biologically and/or by chemical/physical means. Biological phosphorus removal methods involve (a) assimilation of phosphorous (macro-nutrient) into cellular mass, and (b) enhanced phosphorus uptake by culturing phosphorus accumulating organisms (PAOs) in a sequential anaerobic-aerobic process. The latter is done in tertiary processes, such as the Bardenpho, A2O, VIP, and other configurations. A detailed discussion on biological phosphorus removal can be found in MOP-8 (WEF, 2009).

In addition to biological P removal, chemical precipitation along with subsequent filtration is used to remove phosphorus. Chemical addition is typically required to reduce phosphorus concentrations to low effluent TP levels (TP < 0.1 mg/L) using a metal salt, such as alum or ferric. Chemical addition will precipitate inorganic phosphorus. The extent of phosphorus precipitation is largely governed by pH, alkalinity, and the metal dose to orthophosphate ratio. The appropriate pH operating range is based on the coagulant used, whereby alum has a tighter operating range than ferric. Because the process provides both a chemical and physical approach, it provides an extra layer of defense in reliably meeting the TP objective. Recent work has shown that the metal/phosphorus chemistry is closely tied to hydroxide formation that form covalent bonds to metal hydroxides is the major mechanism for

phosphorus removal. A more detailed discussion on the fundamentals of phosphorus chemical precipitation in WWTPs can be found in Snoeyink and Jenkins (1980) and Smith et al. (2008).

2.6.2 Role of Dissolved Organic Nitrogen on Future Permits

A portion of the nitrogen load that enters a municipality is recalcitrant and commonly referred to as refractory dissolved organic nitrogen (rDON). DON in wastewater suffers from a matrix effect that impairs a facility's ability to remove rDON (Lee and Westerhoff, 2005). A survey of over 30 municipal wastewater treatment plants showed that the effluent DON concentrations range from 0.5 to 2 mg/L as nitrogen (WERF, 2008), with values as high as 2.8 mg/L. Given that some permits require nitrogen discharge on the order of 1 mg/L as nitrogen, DON concentrations can govern a municipality's ability to meet permit without the likes of RO.

The chemical compounds that contribute to DON are still largely unknown. Parkin and McCarty (1981) used various size exclusion techniques to characterize rDON, but they only identified roughly 30 percent of the compounds. Recent work by Pehlivanoglu-Mantas and Sedlak (2008) attempted to better characterize and understand rDON. Their findings are largely comparable to the Parkin and McCarty results. Although the composition of rDON is largely unknown, the measured compounds comprised primarily of dissolved free and dissolved combined amino acids (DFAA/DCAA; roughly 10 to 20 percent of effluent DON) (Pehlivanoglu-Mantas and Sedlak, 2006). Dimethylamine (DMA), ethylenediaminetetraacetic acid (EDTA), and nitrilotriacetic acid (NTA) make up the remaining proportion of measured compounds. The remaining ~70% of DON has not been identified and is thought to be bound to other compounds, such as N-functional groups bound to humics (hydrophobic). Refer to the WERF compendium on rDON by Stensel et al. (2008) for more details.

2.6.3 Role of Dissolved Organic Phosphorus on Future Permits

Phosphorus is comprised of various fractions, with the two primary forms as either particulate or soluble. Within each fraction, phosphorus species can be characterized in terms of the analytical method used to measure them. Reactive P (e.g., ortho-P) includes phosphorus species that is measured using a reactive dye and primarily indicate orthophosphates; acid hydrolysable P includes phosphorus that is released under mild acid conditions (e.g. polyP); and total phosphorus includes all phosphorus species detected following a strong acid digestion step (Lei and Gu, 2010). As with nitrogen, there is a fraction of P that is recalcitrant, referred to as recalcitrant dissolved organic phosphorus (rDOP). The compounds that comprise refractory phosphorus are largely unknown.

Currently, phosphorus removal technologies at WWTPs primarily target ortho-P, those compounds that can be converted to ortho-P, or particulates elimination using chemical and/or biological methods. As the discharge permits require more phosphorus removal, the fractions outside reactive P become increasingly important. In particular, the DOP fraction plays a critical role since it is not removed biologically or chemically. The DOP is the difference between acid hydrolysable and total P. Full-scale performance data from various facilities indicate that biological phosphorus removal at WWTPs can achieve an effluent discharge from 0.1-0.3 mg/L (Neethling et al., 2005; Gu et al., 08, Drury et al., 06; Lei and Gu, 2010). Of the remaining phosphorus, chemical phosphorus removal by metal salts is commonly used to increase removal. The additional removal is dependent on the fraction of non-reactive soluble P, chemical dose, pH, as well as the ability to remove the precipitated solids. Based on these uncertainties, it is difficult to supply a range of values achievable by chemical precipitation/filtration.

2.6.4 Greenhouse Gas Emissions at Wastewater Treatment Plants

Some gaseous by-products produced during municipal wastewater treatment are known GHG contributors. The by-products of interest have evolved from only including methane gas (CH₄) (IPCC, 2001) to the incorporation of carbon dioxide gas (CO₂), methane gas (CH₄), and nitrous oxide gas (N₂O) (IPCC, 2006).

Carbon dioxide (CO₂) created during the oxidation of cBOD does not constitute a GHG contributor as the CO₂ is biogenic and thus, not derived from fossil fuels. The three areas that comprise the majority of GHG emissions from a municipality are carbon dioxide (CO₂) emissions from energy demand (e.g., pumping, mixing, and aeration), methane (CH₄) in the collection system and anaerobic digestion, and nitrous oxide (N₂O) emissions during biological treatment.

Outside of the energy demand associated with pumping, mixing, and aeration, the corresponding subsections provide background information on other key areas of GHG emissions at WWTPs.

2.6.4.1 Carbon Dioxide (CO₂) Production in Wastewater Processes

Natural sources of atmospheric CO₂ that cycle from plants to animals to humans as part of the natural carbon cycle and food chain are excluded from global warming potential calculations. This natural source of atmospheric CO₂ is commonly referred to as short-cycle atmospheric CO₂. As previously mentioned, this CO₂ contributor is commonly referred to as biogenic carbon. Photosynthesis removes an equal mass of CO₂ from the atmosphere that returns during respiration or wastewater treatment. The conversion of cBOD to CO₂ during secondary treatment falls under biogenic carbon. Digestion processes, either aerobic or anaerobic, also only emit short-cycle CO₂. Nutrient removal, compared to carbonaceous treatment only, or even nitrification treatment, generates comparable quantities of short-cycle CO₂. CO₂ emissions in the receiving water from effluent biochemical oxygen demand (BOD) also qualifies as short-cycle.

2.6.4.2 Energy Demand at Wastewater Treatment Plants

Energy is by far the largest contributor to GHG emissions at WWTPS (Keller and Hartley, 2007; Tripathi, 2007). As will be presented in Chapter 5.0, energy represents over 80 percent of the total (Scope 1, 2 and 3) GHG emissions at a WWTP. At most plants, electrical energy dominates. However, many plants also use significant quantities of natural gas. Electrical energy is a scope 2 emission and the GHG associated with electricity is from the CO₂, N₂O and CH₄ produced by combustion of fossil fuels at the electric utility. Consumption of natural gas for process and building heat as well as power generation is a scope 1 emission.

2.6.4.3 Methane (CH₄) Production in Wastewater Processes

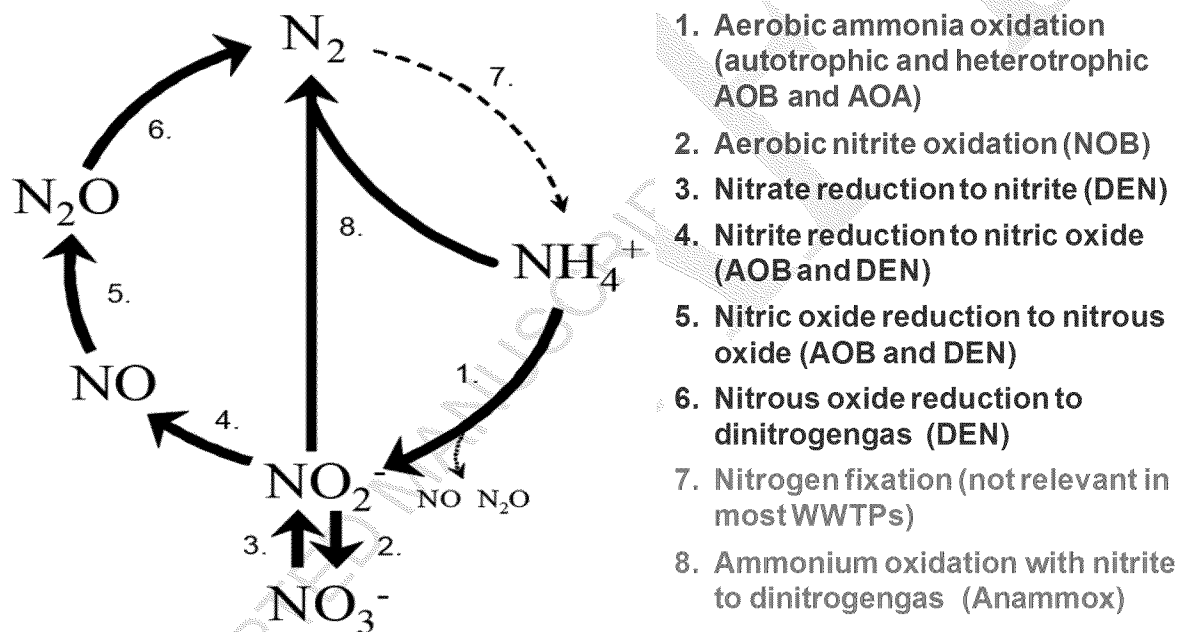
Methane formation at WWTPs is largely ignored in GHG calculations as suggested in the IPCC methane fugitive methane emissions empirically based multipliers (IPCC, 2006). Anaerobic conditions that promote methane formation within a WWTP may exist in the collection system, primary clarifiers, anaerobic selectors, improperly aerated aeration basins, anaerobic digesters (intentional), digested sludge dewatering (gas or in filtrate/centrate), and in the effluent stream (through BOD degraded anaerobically in receiving waters). Despite all these different locations for potential methane formation in a WWTP, it is thought to yield a minimal

contribution within the boundaries of a WWTP. This report assumes the IPCC (2006) multipliers for all levels.

2.6.4.4 Nitrous Oxide (N₂O) Production in Wastewater Processes

Nitrous Oxide (N₂O) is one of the important gases considered by the Intergovernmental Panel on Climate Change (IPCC) for its greenhouse gas emission scenarios (IPCC, 2000). This is understandable given that the greenhouse impact of N₂O is about three hundred times that of CO₂. Notwithstanding the recognized impact of N₂O and the acknowledged role of wastewater treatment in its generation, there are few studies that attempt to explicitly determine the impact of global wastewater treatment strategies on actual climate change indicators.

In the case of biological nitrogen removal facilities (i.e., nitrification and denitrification), N₂O emissions occur during both nitrification/denitrification. Figure 1 (Kampschreur et al., 2008) shows potential biological transformations pathways of nitrogen and how N₂O potentially forms during nitrification and always forms as a denitrification intermediate.



Complete Nitrification: Step 1 and 2

Complete Denitrification: Step 3 to 6

Figure 1. Biological Nitrogen Conversions (N pathway borrowed from Kampschreur et al., 2008)

Recent studies by Yu et al. (2010) evaluated the mechanisms of N₂O emissions for ammonia oxidizing bacteria (AOB). The studies found that AOB produce N₂O based on AOB recovery from anoxic to oxic conditions coupled with ammonia accumulation in the anoxic phase. The extent of N₂O emissions is less pronounced in reactors that contain the symbiotic bacteria populations of AOB and nitrite oxidizing bacteria (NOB) than by their individual populations (Kester et al., 1997). As for the heterotrophic denitrifiers that perform denitrification in WWTP anoxic zones, the biokinetic rate of N₂O emissions is a 2nd order function of NO

accumulation (Girsch et al., 1997). The NO accumulation is a function of DO levels in the anoxic zone.

Data on N₂O emissions was collected from 12 different activated sludge facilities in the United States by Ahn et al. (2010). Their findings suggest that reactor configuration (e.g., MLE, oxidation ditch, step feed, etc.) plays a role in the concentration of N exiting the municipality as N₂O with values ranging from 0.03 (separate stage BNR) to 1.8 (step feed non-BNR) percent of the influent TKN load. Given the wide range of N₂O emission values, this White Paper will utilize the N₂O emission values developed by IPCC (2006). It should be noted that the results by Ahn et al. (2010) show that WWTPs can have an order of 1 magnitude or greater than IPCC (2006) predictions. The authors recognize that although this approach is not based on data from WWTP, it is based on a platform currently recognized as the standard.

2.6.4.5 External Carbon Source Selection

The ability to achieve low total nitrogen levels (TN < 8mg/L) typically requires an external carbon source for denitrification. Historically, methanol has been the most commonly utilized carbon source for tertiary denitrification processes for economic reasons as well as relatively low solids yields. During the past several years, there has been an increased focus on alternative carbon sources. The interest in alternative carbon sources is due to safety concerns associated with methanol, increases in methanol costs, and lapses in its availability.

There has been significant research into denitrification kinetics, biomass yields, and operating issues associated with these carbon sources. More detailed information on the use of alternative carbon sources can be found in a separate WERF Compendium on carbon augmentation for biological nutrient removal (Sandinho et al., 2008).

This report assumes methanol as the external carbon source for all levels. Although methanol is a natural fuel, it is fossil based and its use as a substrate requires chemical manufacturing. Thus, it is considered a GHG in WWTP audits and factored into the calculations. The chemical production of methanol yields 0.67 lb CO₂ per lb methanol (Willis et al., 2009). This GHG value does not include the hauling of chemical from the manufacturing facility to its end use location.

2.6.4.6 Chemicals

Wastewater treatment requires a variety of chemicals for flocculation, coagulation, disinfection, solids thickening and dewatering, and a carbon source for growth. In particular, WWTPs with low level nitrogen and phosphorus permits require an external carbon source and metal salt, respectively. Although the role of chemicals on GHGs is excluded scope 1 and 2 emissions, they are included in scope 3 emissions.

An area of chemical usage largely overlooked at WWTPs is the GHG emissions associated with their production and transportation. It is critical that the amount of GHGs associated with each individual chemical during production is incorporated into the evaluation. Additionally, the distance travelled, fuel type, and truck fuel efficiency all play a role in quantifying their respective GHGs. This report utilizes the chemical production values from Tripathi (2007) and the IPCC (2007) hauling values.

2.6.4.7 Brine Production/Management

For the most stringent permit level listed in the five-tier objectives (Table 1), Level 4 would require side-stream reverse osmosis (RO) due to the inability to remove the previously mentioned rDON. The RO process concentrates contaminants into a smaller volume of brine. Brine disposal can be problematic due to the potentially large volume of water involved and the concentration of contaminants contained in the brine. The primary treatment/handling options for RO reject are as follows:

- ☐ surface water or ocean discharge
- ☐ haul and discharge to coastal location for ocean discharge
- ☐ sewer discharge
- ☐ deep well injection
- ☐ evaporation pond
- ☐ solar pond concentrator
- ☐ advanced thermal evaporation

It is important to recognize that despite several different alternatives to treat brine reject, the solutions are geographically specific. For example, a surface water discharge to the ocean by a coastal city is a viable option for coastal cities. In contrast, surface water discharge to the ocean by an inland city is not an option. A brief description for each brine management alternative is provided below. For a more detailed breakdown on sizing and their capital construction costs refer to Mickley et al. (2006).

Surface Water or Ocean Discharge

Surface water discharge is typically the most cost-effective method for brine disposal. Implementation typically requires storage (above-ground or lined pond). The storage equalizes discharge flow, provides solids settling, and/or cools the waste discharge.

Sewer Discharge

Discharging to a sewer is a common brine disposal method in urbanized areas and can be equal or less than the cost of surface water discharge. The wastewater agency receiving the brine would require an analysis to determine the impacts on the collection system hydraulic capacity and the biological processes at the treatment plant. In addition, an assessment of how the elevated TDS levels associated with the brine reject would impact the sewers, lift stations, and force mains.

Deep Well Injection

Deep well injection (DWI) of reject brine is widely used in the oil industry and to relocate saline groundwater and protect fresh water aquifers. Deep well injection can provide a safe means of permanent brine disposal because the brine is sequestered from potential drinking water aquifers. However, some desalination facilities, as well as oil and gas companies, have rejected the deep well injection method because these wells are difficult to permit and maintain. A Class 1 or Class 5 nonhazardous well permit (as defined by EPA) would be required for brine

purge disposal. Furthermore, very high pressures (and energy) may be required for deep well injection.

Evaporative Pond

Evaporation ponds offer a reliable, “low-tech” method to concentrate the high strength waste stream and potentially reduce hauling and disposal costs. Although effective, evaporation ponds are considered to be land intensive. However, evaporation ponds can be used in tandem with other technologies, such as thermal concentrators, to reduce land requirements.

Driving factors for evaporation ponds are area demands, flows, flow composition, and meteorological conditions. It is estimated that the high strength waste stream (> 20% TDS) will evaporate at a 30 percent slower rate than fresh water and consequently requires more acreage on a flow per unit area basis. Although evaporative ponds are reliable, local climate conditions, urban area land needs, and relatively high land costs can reduce their viability.

A key issue not dealt with the previous three brine management strategies is how to deal with the final concentrated salt product. At some point, the evaporative pond reaches capacity and requires the salt be managed. Typically, the salt is crystallized, packaged in plastic containers and disposed of by hauling to a landfill.

Salinity Gradient Solar Pond

The Salinity Gradient Solar Pond (SGSP) provides an alternative, less land intensive approach to evaporation ponds. While evaporative ponds attempt to drive moisture away by solar evaporation, SGSPs are designed to harness the solar power within the pond to power a multi-staged evaporative unit, such as a multi-effect distillation (MED) unit. In addition to a concentrate stream, a condensation stream (i.e., distilled water) is collected with the MED unit that can be used for other on-site reuse applications.

Like the evaporative pond how to deal with the final concentrated salt product is problematic. At some point, the SGSP fills and subsequently requires salt management. Typically, the salt is crystallized, packaged in plastic containers, and disposed of by hauling to a landfill.

Advanced Thermal Evaporation

Advanced thermal evaporation requires a two-step process consisting of a brine concentrator followed by crystallizer. In terms of space requirements, a brine concentrator followed by crystallizer is the most compact approach for concentrating the brine purge stream. The crystallized product can be hauled to a landfill for ultimate disposal.

Summary

There are many techniques to manage brine associated with RO reject. The appropriate alternative is primarily governed by geography. A listing of the relative brine management costs is provided in Table 4.

Table 4. Relative Disposal Method Cost Comparison

Disposal Method	Relative Capital Cost	Relative O&M Cost	Comments
Surface Water Discharge	Lowest	Lowest	Both capital and O&M costs heavily dependent on the distance from brine generation point to discharge.
Sewer Discharge	Low	Low	Both capital and O&M costs heavily dependent on the

Disposal Method	Relative Capital Cost	Relative O&M Cost	Comments
Deep Well Injection	Medium	Medium	distance from brine generation point to discharge. Higher cost than surface water discharge due to ongoing sewer connection charge. Technically sophisticated discharge and monitoring wells required. O&M cost highly variable based on injection pumping energy.
Evaporation Ponds	Low – High	Low	Capital cost is highly dependent on the amount and unit cost of land.
Salinity Gradient Solar Ponds	Low – High	Lowest	Same as evaporation ponds plus added cost of heat exchanger and pumps. Lower O&M cost due to electricity production.
Advanced Thermal Evaporation	High	Highest	Extremely small footprint, but the energy associated with H ₂ O removal is by far the most energy intensive unless waste heat is used.

Of the listed options, the capital costs associated with DWI is comparable nationwide as it requires drilling and pumping. In contrast, an evaporation pond cost is dependent on the acreage costs. Based on the normalized capital costing of DWI, we considered it for this investigation. It is important to recognize that the impact of brine management on GHG emissions is highly variable for the seven listed options above.

2.7 Example of GHG Inventory Performed on WWTP

An example of Scope 1 and 2 emission results for a municipality is provided in this subsection as a means to show the steps associated with performing a GHG audit on a municipality. The example used is for the Easterly WWTP located in Vacaville, CA. The GHG emissions and carbon footprint boundary for this analysis is defined as operations within the property bounds. To re-iterate Section 2.4, Scope 1 and 2 emissions include the following:

- ☐ **Scope 1 – Direct on-site GHG emissions. These are generally described as anthropogenic GHG (those related to man’s activities):**
 - ☐ On site production of electricity, heat or steam using fossil fuels
 - ☐ Physical or chemical processing
 - ☐ Transportation of materials, products, waste, and employees
 - ☐ Fugitive emissions
 - ☐ Natural gas combustion
- ☐ **Scope 2 – Indirect GHG emissions from imports (or purchases) of electricity, heat, or steam.**

Besides pointing out what is included, it is critical to point out what this example excludes:

- ☐ Scope 3 supply chain sources
- ☐ Wastewater collection system
- ☐ Effluent discharge to receiving water
- ☐ Fugitive emissions
- ☐ Biosolids emissions at the landfill (although the diesel fuel to transport the biosolids to the local landfill was counted as a mobile source)

2.7.1 Accounting and GHG Emissions Boundary Conditions for Easterly WWTP

Table 5 below outlines the accounting for GHG emissions at the Easterly WWTP.

Table 5. Summary of GHG Emissions Accounting at the Easterly WWTP

GHG Emission Type	GHG Emission Calculated for the Easterly WWTP
Scope 1 - Direct – Stationary	CO ₂ eq emissions from testing/operating on-site generators Emissions from natural gas combustion
Scope 1 - Direct – Mobile	CO ₂ eq emissions from plant operations and maintenance vehicles
Scope 1 - Direct – Process	N ₂ O from nitrification and NDN processes CH ₄ from anaerobic digester flare inefficiencies Cogeneration produced by digester gas
Scope 2 – Indirect	CO ₂ eq from purchased electricity

Calculations of these GHG emissions are summarized below.

2.7.2 Base Year and Future Years Used for GHG Emissions

A GHG emission inventory was developed for different alternatives as shown in Table 6. The alternatives consider conditions in 2008, followed by future flows and loads, with and without nitrogen removal, and with and without cogeneration. The future conditions are for years 2014 and 2035.

Table 6. Base Year and Future GHG Calculation Scenarios, Vacaville, CA

Inventory	Time Period (annual average flow)	Description of Treatment Scenario of Influent Wastewater to the Easterly WWTP
1	Base Yr 2008 (9 mgd)	Flow treated at Easterly WWTP cBOD mode NO cogeneration Existing treatment process
2	Future Yr 2014 (9 mgd) NDN Upgrades Complete	Flow treated at Easterly WWTP Cogeneration added NDN added to treatment process
3	Future Yr 2035 (15 mgd) NDN Upgrades Complete	Flow treated at Easterly WWTP Cogeneration added NDN added to treatment process
4	Future Yr 2035 (22.9 mgd) Existing Processes	Flow treated at Easterly WWTP NO cogeneration Existing treatment process This inventory was done at the direction of the EIR consultant

5	Future Yr 2014 (9 mgd) NDN Upgrades Complete	Flow treated at Easterly WWTP NO cogeneration NDN added to treatment process
6	Future Yr 2035 (15 mgd) NDN Upgrades Complete	Flow treated at Easterly WWTP NO cogeneration NDN added to treatment process

2.7.3 Emission Calculations

The emissions were calculated using the Local Government Operations Protocol (Ver. 1.1) and the Climate Registry General Reporting Protocol (Ver. 1.1). For the purposes of the analyzed inventories, default CO₂ eq multiplication factors of 21 and 310 were used for CH₄ and N₂O, respectively, per the above protocols.

Scope 1 - Direct Stationary – Direct stationary emissions at the Easterly WWTP are limited to natural gas and the emergency standby generators used for back-up power.

Natural gas is used for building heating in the Admin/Lab Building, Maintenance Building, and Boiler/Heat Exchanger.

Scope 1 - Direct Mobile – Direct mobile emissions at the Easterly WWTP were calculated for on-site vehicles associated with the facility's routine operations and maintenance work. An estimate for daily miles traveled both in the base and future years was utilized to develop GHG emissions.

Scope 1 - Direct Process – The liquid treatment process GHG emissions include nitrification and de-nitrification (NDN) processes in the activated sludge system. The anaerobic digester gas produced is either used by the cogeneration process or flared, depending on the inventory scenario. These types of digester gas flares offer some inefficiency in combustion of the gas which is considered in the GHG emissions calculations.

Scope 2 – Indirect – Purchased Electricity - Indirect emissions related to Easterly WWTP operations include the purchase of electricity. Purchase of electricity is typically the most significant GHG emission from wastewater treatment facilities. To determine baseline power use, historical energy consumption was evaluated for Easterly WWTP. Recent historical energy use reflects current operations and supports development of the baseline (Inventory 1) indirect GHG emissions.

2.7.3.1 Methodology

Inventories were developed for the various Scope One emissions (digester gas flaring, mobile sources, stationary combustion, and nitrification) and Scope Two emissions (electrical consumption). Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions were determined using the above protocols. The equivalent CO₂ emissions were subsequently calculated using standard protocol conversions (see Basis of Calculations below). The total equivalent CO₂ emissions were then compiled using contributions from each source and summarized at the end of this document. Scope 1 and Scope 2 emissions were analyzed for these inventories.

2.7.3.2 Basis of Calculation

The inventory calculations were based on the following:

- ☐ The EWWTP fuel, electric, and digester gas consumption increases by a factor of 1.67 from the 9 mgd to 15 mgd levels
- ☐ The 2008 City of Vacaville population level was 96,450
- ☐ The 2035 City of Vacaville population level is estimated to be 132,300
- ☐ The digester gas electrical cogeneration facility will be operational during Inventory #2 and #3
- ☐ The digester gas electrical cogeneration facility would not be operational during Inventory #4, #5 and #6
- ☐ The CO₂ equivalent multiplier is 21 for methane (CH₄) and 310 for nitrous oxide (N₂O)

The GHG emissions for the scenarios evaluated are summarized in Table 7.

Table 7. Easterly WWTP – GHG Emissions Summary (mtCO₂ eq/yr) – Scope 1 and 2

Scenario	Results
Inventory #1: Existing Conditions w/cBOD mode	4,690 metric tons/year (equivalent CO ₂)
Inventory #2: 9 mgd w/ Nitrification/ Denitrification & Cogeneration System	4,550 metric tons/year (equivalent CO ₂)
Inventory #3: 15 mgd w/ Nitrification/Denitrification & Cogeneration System (Cumulative Year 2035)	7,540 metric tons/year (equivalent CO ₂)
Inventory #4: 15 mgd using Current Processes (Cumulative Year 2035)	7,780 metric tons/year (equivalent CO ₂)
Inventory #5: 9 mgd w/ Nitrification/Denitrification (No Cogeneration System)	5,170 metric tons/year (equivalent CO ₂)
Inventory #6: 15 mgd w/ Nitrification/Denitrification (No Cogeneration System) (Cumulative Year 2035)	8,570 metric tons/year (equivalent CO ₂)

CHAPTER 3.0 - REGULATIONS AND DRIVING FORCES

3.1 Introduction

Nutrient removal treatment can substantially reduce point source discharges of nitrogen and phosphorus. Substantial investments are required to build and operate advanced wastewater treatment facilities. Nitrogen and phosphorus loadings to watersheds impact water quality by stimulating the growth of algae which may result in depletion of dissolved oxygen, shifts in pH, degradation of habitat, impairment of drinking water sources, and in some cases harmful algal blooms (USEPA, 2010). According to the EPA, nearly every State has nutrient related pollution with impacts in over 80 estuaries/bays, and thousands of rivers, streams, and lakes. In particular, EPA cites the Gulf of Mexico and the Chesapeake Bay as examples of significant water quality impacts from 35 States that contribute to nutrient loadings.

Nutrient loadings from both point and nonpoint sources contribute to water quality impairments in the nation's waterways. Point source discharges from wastewater treatment plants can be a significant source of nitrogen and phosphorus in watersheds. Nonpoint sources also contribute substantial amounts of nutrients from land use activities such as agriculture, forestry, and urban/suburban development. In some watersheds, nonpoint source nutrient loadings outweigh point sources to a degree that advanced treatment for nutrient removal, and even complete elimination of point sources, would have limited benefit to water quality. Nevertheless, point source NPDES permitted dischargers are the most directly regulated sources subject to nutrient control requirements resulting from numeric nutrient standards, total maximum daily loads (TMDLs), and water quality based permit limits.

3.2 EPA Numeric Nutrient Standards

EPA efforts to promulgate numeric nutrient standards in all states have raised a number of questions about how these standards will be applied to wastewater dischargers. The EPA initiated an effort in 1998 with a goal of adopting numeric nutrient standards in all states by 2002. This goal has not been accomplished. On May 25, 2007, the EPA Assistant Administrator, Ben Grumbles, issued a memorandum entitled "Nutrient Pollution and Numeric Water Quality Standards" to State and Tribal water program directors. The memo provides an update on the EPA's commitment to accelerating the development of numeric nutrient water quality standards.

Some States and Territories have made notable progress since then, but overall results have been inconsistent.

Ben Grumbles (USEP Assistant Administrator) noted that high nitrogen and phosphorus loadings result in harmful algal blooms, reduced spawning grounds and nursery habitats, fish kills, oxygen-starved hypoxic or “dead” zones, public health concerns related to impaired drinking water sources, and increased exposure to toxic microbes, such as *Cyanobacteria sp.* The most widely known examples of significant nutrient impacts include the Gulf of Mexico and the Chesapeake Bay.

Descriptions of four watersheds of particular importance are included in the memo:

- Chesapeake Bay has an existing hypoxia problem and adds 150,000 new people a year to the watershed.
- The Gulf of Mexico has a prevalent and well-documented hypoxic “dead” zone. Thirty-one states contribute to the watershed and, through the 2001 Hypoxia Action Plan, the EPA Science Advisory Board reports that phosphorus plays a much greater role in the hypoxia problem than previously thought.
- In the Long Island Sound, DO is below standards in one-third to one-half of the Sound. Nitrogen loadings have been capped at 1990 loads, and a water quality trading program has been implemented in Connecticut for point sources with a market-based approach.
- In Puget Sound, the highest priority is to gain a better understanding of nutrient and bacteria loadings from septic systems through the Puget Sound Action Plan.

3.3 New Voices in the Nutrient Impact Discussion-NRDC and Others

The national discussion of nutrient impacts on water quality is evolving and is highlighted by issues in high visibility water bodies such as the Chesapeake Bay, Long Island Sound, the Gulf of Mexico, and Puget Sound, as indicated above. New organizations have entered the discussion and some have called for treatment technology standards for nitrogen and phosphorus.

In November 2007, the Natural Resources Defense Council (NRDC) filed a Petition for Rulemaking with the EPA to limit nutrient pollution from wastewater treatment facilities. Ten other regional and national environmental groups, including the Sierra Club and American Rivers, joined NRDC in the petition. NRDC argues that nitrogen and phosphorus effluent limitations should be a part of the base technology definition of secondary treatment. NRDC contended that the EPA must protect the public by establishing nutrient limits, specifically that the EPA unreasonably delayed publishing information on Secondary Treatment to remove excess nutrients. The NRDC also notes that nutrient control is properly included within “Secondary Treatment” and cites the following effluent nutrient levels as attainable:

- Effluent TP 1 mg/l and TN 8.0 mg/l is Attainable with Existing Technology Using Only Improved Biological Treatment Processes
- Effluent TP 0.3 mg/l and TN 3 mg/l are Consistently Attainable Using Current Technology

NRDC considers the EPA's approach to site-specific nutrient standards as unreasonable and that the EPA cannot rely on a water-quality based approach to control nutrient pollution. NRDC argues that nutrient pollution is widespread and justifies a generally-applicable standards approach. NRDC calls for the EPA to specify the degree of nitrogen and phosphorus reduction attainable through secondary treatment.

The National Association of Clean Water Agencies (NACWA) provided comments on the NRDC Petition for Rulemaking on Secondary Treatment in a letter to EPA dated February 29, 2008 (NACWA 2008). NACWA expressed concern that the NRDC petition calling for nutrient limits as part of the secondary treatment process is not technically or financially practical, and that the approach is not the most effective or environmentally sensitive way to reduce nutrient pollution. NACWA criticize the proposed "one size fits all" approach to a water quality problem that is site-specific and best to address site-specific measures.

NACWA believes site specific water quality efforts will be more effective than technology based nutrient removal limits and cites five areas of concern with the NRDC Petition:

1. Legal basis for incorporating nutrient removal into secondary treatment
2. Failure of the petition to address the contribution to nutrient loadings from non-point sources
3. Potentially high costs for treatment plants to meet a national nutrient limit and whether such expenditures are cost-effective
4. Increased negative environmental impacts of mandating a national nutrient removal limit
5. Inappropriateness of national limits for local and regional water quality issues

NACWA notes that tertiary treatment for nutrient removal goes well beyond the original Congressional intent in the Clean Water Act for secondary treatment and that EPA has denied previous request to include nutrient removal as part of secondary treatment standards. NACWA states that the petition fails to acknowledge the impact of nonpoint sources of nutrients on water quality. NACWA members have found that the costs for nutrient removal are substantial and that major expenditures are associated with expanding facilities because of the need for more plant site space to accomplish retrofits.

3.4 The Ecoregion Concept and Nutrient Criteria

The concept of ecological regions, or ecoregions, is the grouping of areas of similar climate, hydrology, geology, physiography, soils, land use, vegetation, and wildlife. The ecoregion criteria concept was included in the National Strategy for the Development of Regional Nutrient Criteria from the beginning, citing the work of James Omernik of the EPA Corvallis, OR laboratory. There are four levels of ecoregions, with Level I being the coarsest and Level IV the most detailed. Fourteen ecoregions in the continental United States are Level I, while 104 are Level III as shown in Figure 2.

The EPA has established criteria for total phosphorus and total nitrogen for Level I ecoregions for rivers and streams, lakes and reservoirs, and wetlands. "The nutrient criteria presented by the EPA for each ecoregion are generally based on the 25th percentile value of all data from the respective ecoregion. The 25th percentile value corresponds to the concentration

at which 25 percent of the measured values are below and 75 percent of the measured values are above" (EPA, 2000). A summary of the rivers and streams criteria are shown in Table 8.

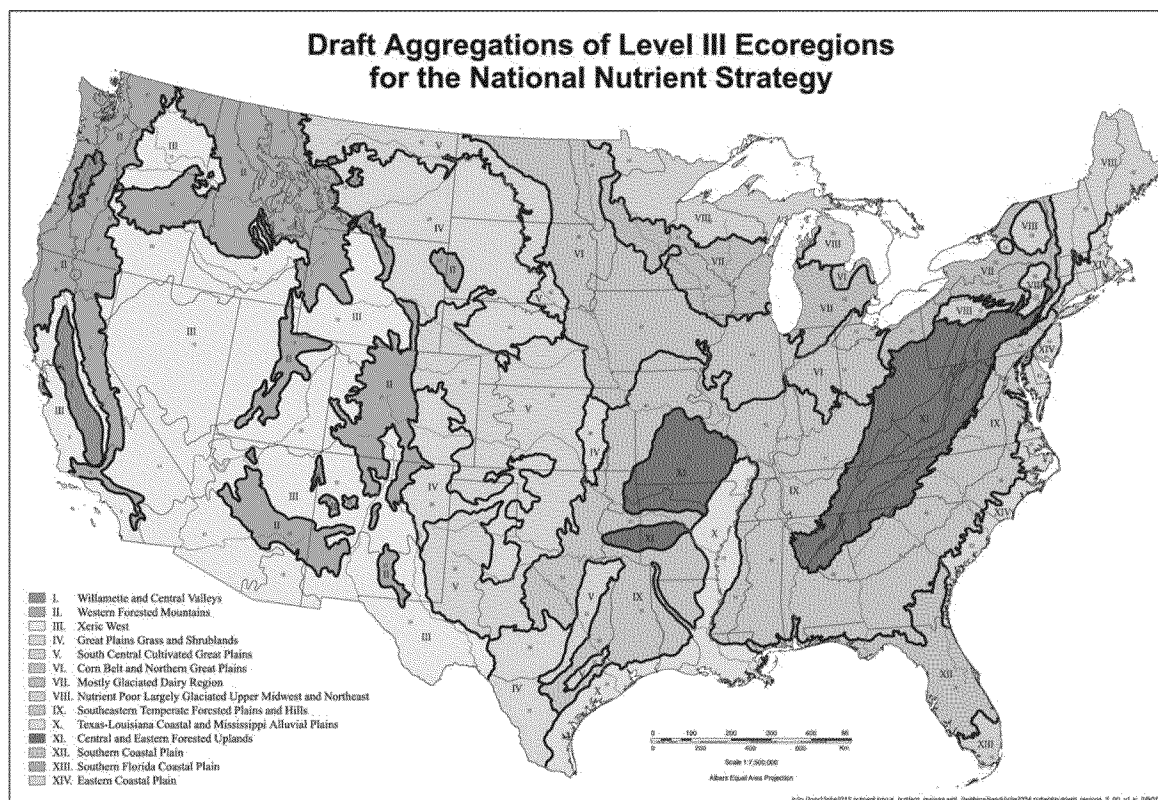


Figure 2. EPA Level III Ecoregions

The values in Table 8 are broken up into two columns per constituent with the first supplying the in-stream nutrient level and the second the value discharged from the WWTP for a 20:1 dilution. The 20:1 dilution credit was used because a less dilute discharge is considered a wastewater dominated stream. The corresponding required treatment level for the 20:1 dilution is provided in Table 8.

Table 8. Summary of Ecoregion Criteria for Rivers and Streams

Ecoregion	TN (mg/L) IN-STREAM	TN (mg/L) DISCHARGE (20:1 Dilution)	TP (mg/L) IN-STREAM	TP (mg/L) DISCHARGE (20:1 Dilution)	Treatment Level (20:1 Dilution)
I: Willamette and Central Valley	0.66	13.2	0.055	1.1	Level 1
II: Western Forested Mountains	0.12	2.4	0.010	0.2	Level 4
III: Xeric West	0.38	7.6	0.022	0.44	Level 2
IV: Great Plains Grass and Shrublands	0.56	11.2	0.023	0.46	Level 2

Ecoregion	TN (mg/L) IN-STREAM	TN (mg/L) DISCHARGE (20:1 Dilution)	TP (mg/L) IN-STREAM	TP (mg/L) DISCHARGE (20:1 Dilution)	Treatment Level (20:1 Dilution)
V: South Central Cultivated Great Plains	0.88	17.6	0.067	1.34	Level 1
VI: Corn Belt and Northern Great Plains	2.18	43.6	0.076	1.52	Level 1
VII: Mostly Glaciated Dairy Region	0.54	10.8	0.033	0.66	Level 2
VIII: Nutrient-Poor, Largely Glaciated Upper Midwest and Northeast	0.38	7.6	0.010	0.2	Level 2
IX: Southeastern Temperature Forested Plains and Hills	0.69	13.8	0.037	0.74	Level 2
X: Texas-Louisiana Coastal and Mississippi Alluvial Plains	0.57	11.4	0.060	1.2	Level 1
XI: The Central and Eastern Forested Uplands	0.31	6.2	0.010	0.2	Level 3
XII: Southeastern Coastal Plain	0.90	18	0.040	0.8	Level 2
XIII: Southern Florida Coastal Plain	1.14	22.8	0.015	0.3	Level 2
XIV: Eastern Coastal Plain	0.71	14.2	0.031	0.62	Level 2

3.5 Effluent Technology Limits Do Not Guarantee Water Quality

Increased levels of treatment for nutrient removals do not guarantee receiving water quality improvements. Water quality is impacted by many factors with complex relationships in the aquatic environment, including the magnitude of pollutant loading compared to the receiving waters, limiting nutrients that control aquatic growth, and receiving water physical characteristics. Much focus has been placed on point sources for control of nutrient discharges, where point sources are only a part of the nutrient loading picture. EPA now recognizes that most watersheds are impaired by a combination of point and non point sources. In fact, EPA indicates that point sources may be contributing only a small fraction of water quality impairment as shown in Figure 3, Figure 4, Figure 5 (Clark, 2009).

Sources of Impairment by Category from the 1998 303(d) List

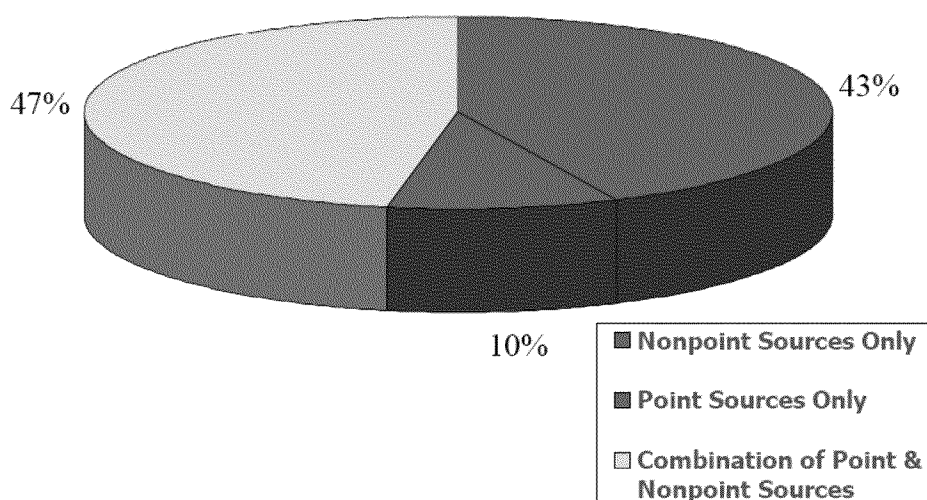
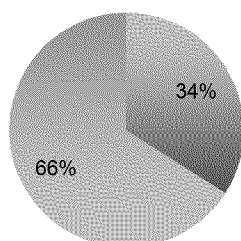


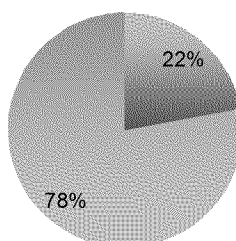
Figure 3. Sources of Water Quality Nationwide from EPA (Source: Total Maximum Daily Load Program, EPA Region 4, January 2001)

Gulf of Mexico
Phosphorus Sources



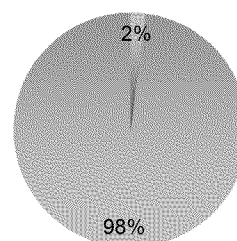
■ Point Sources
■ Non-Point Sources

Chesapeake Bay
Phosphorus Sources



■ Point Sources
■ Non-Point Sources

Flathead Lake
Phosphorus Sources



■ Point Sources
■ Non-Point Sources

Figure 4. Phosphorus Loading Summaries for Gulf of Mexico, Chesapeake Bay, and Flathead Lake

(Sources: Gulf of Mexico Hypoxia 2008 Action Plan, Chesapeake Bay Program Action Plan, Montana Department of Environmental Quality, Draft Nutrient Management Plan and Total Maximum Daily Load for Flathead Lake, Montana)

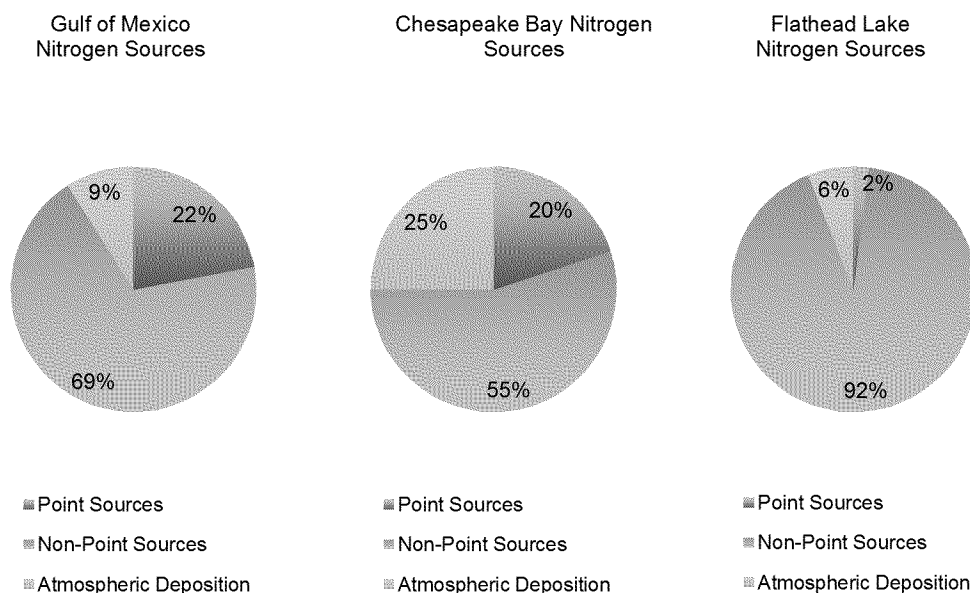


Figure 5. Nitrogen Loading Summaries for Gulf of Mexico, Chesapeake Bay, and Flathead Lake
(Sources: Gulf of Mexico Hypoxia 2008 Action Plan, Chesapeake Bay Program Action Plan, Montana Department of Environmental Quality, Draft Nutrient Management Plan and Total Maximum Daily Load for Flathead Lake, Montana)

Reducing point sources alone may have minimal impact of receiving water quality. Costs and sustainability impacts dramatically increase for treatment facilities with little added value to the environment. A comprehensive approach to point and not point nutrient discharges will yield the most practical solution to improving water quality in our watersheds.

3.6 Summary

There are a number of unintended negative environmental and sustainability consequences of requiring blanket nutrient removal in terms of carbon footprint and increased quantities of biosolids for disposal/reuse. Nutrient removal treatment requires substantial additional electrical power, increased use of chemicals, more process structures, larger biosolids handling/reuse investments, and increased labor. All of this impacts capital and operating costs and sustainability as measured by carbon footprint, especially GHGs. The adverse impacts of point source nutrient controls should be balanced with consideration of nonpoint source controls, which consume little energy and may reduce greenhouse gas emissions by sequestering carbon.

This WERF White Paper will determine these sustainability impacts for five different nutrient removal process arrangements.

CHAPTER 4.0 - FIVE TIERED LEVELS OF TREATMENT, DESIGN CRITERIA, GHG CONVERSION ASSUMPTIONS, AND BOUNDARY CONDITIONS

4.1 Five Tiers Concept

Five different target objectives were developed as shown in Table 9. A baseline case was included, referred to as Level 0, which is a carbonaceous removal facility with primary, secondary, and disinfection on the liquid stream. As for Levels 1 to 4, all facilities have tertiary treatment in the form of biological nutrient removal plus additional tertiary physical/chemical treatment technologies depending on the effluent objective. The nutrient removal values selected are based on the future wide range of values anticipated by stakeholders, such as the USEPA, NRDC, grassroots organizations, etc.

Table 9. Treatment Levels Objectives

Level	Biochemical Oxygen Demand (mg/L)	Total Suspended Solids (mg/L)	Total Nitrogen as Nitrogen (mg/L)	Total Phosphorus as Phosphorus (mg/L)
0	30	30	<30	<30
1	-	-	8	1
2	-	-	4-8	0.1-0.3
3	-	-	3	<0.1
4	-	-	1	<0.01

Treatment unit processes associated with each level is shown in Table 10. Schematics and background of each individual treatment level are provided in subsections.

Table 10. Unit Processes per Treatment Level

Level	Liquid Treatment	Solids Treatment	Comments
0	Primary Clar. Act. Sludge Disinfection Dechlorination	Gravity Belt Thickener Anaer. Digestion with Cogen Centrifugation	Conventional Activated Sludge
1	Primary Clar. Act. Sludge	Gravity Belt Thickener Anaer. Digestion with Cogen	Nitrification/Denitrification with MLE

Level	Liquid Treatment	Solids Treatment	Comments
2	Alum (optional) Disinfection Dechlorination	Centrifugation	Nitrification/Denitrification with MLE plus filtration
	Primary Clar. Act. Sludge Methanol (optional) Alum (filtration) Filtration Disinfection Dechlorination	Gravity Belt Thickener Anaer. Digestion with Cogen Centrifugation	
3	Primary Clar. Act. Sludge Methanol (optional) Alum/Polymer (Enhanced Settling) Enhanced Settling Filtration Disinfection Dechlorination	Fermentation Gravity Belt Thickener Anaer. Digestion with Cogen Centrifugation	Nitrification/Denitrification with MLE plus high rate clarification and filtration
4	Primary Clar. Act. Sludge Methanol (optional) Alum (filtration) Filtration Micro-filtration Reverse Osmosis Disinfection Dechlorination	Gravity Belt Thickener Anaer. Digestion with Cogen Centrifugation	Nitrification/Denitrification with MLE plus high rate clarification, filtration, and side-stream RO

4.1.1 Level 0 (30 mg/L BOD; 30 mg/L TSS; no nutrient requirements)

As previously acknowledged, Level 0 serves as a base case with the traditional cBOD and TSS removal facility. A schematic of treatment Level 0 is shown in Figure 6.

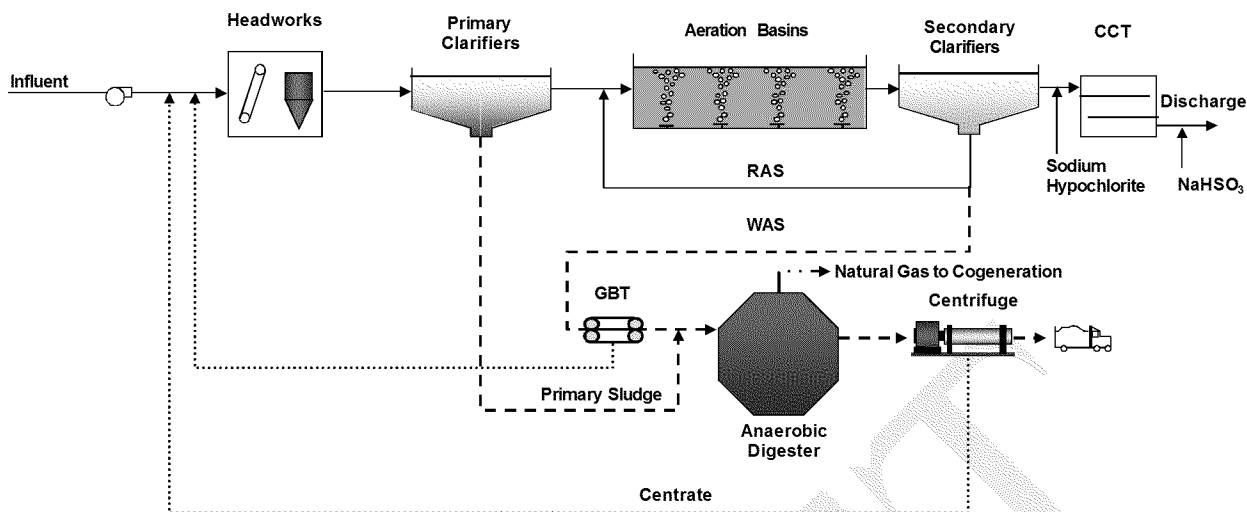


Figure 6. Level 0 Plant Schematic

Besides primary and secondary treatment, disinfection prior to discharge, as well as solids treatment is provided. Solids treatment entails thickening by gravity belt thickener (GBT), anaerobic digestion, and dewatering by centrifuge. The natural gas produced during anaerobic digestion will be used as an energy source for cogeneration using an engine with a jacket and exhaust heat recovery.

4.1.2 Level 1 (8 mg/L N; 1 mg/L P)

The Level 1 treatment facility represents the least stringent of four nutrient removal facilities. A schematic of treatment Level 1 is shown in Figure 7. The secondary treatment facility consists of a conventional type biological nutrient removal process, whereby the first zone is anaerobic, followed by anoxic and aerobic zones (example processes are A2O, MLE, 4-stage and 5-stage Bardenpho, Oxidation Ditch, etc.). The mixed liquor return (MLR) carries nitrified water from the aerobic phase to the anoxic phase for denitrification. Alum addition is optional prior to the secondary clarifiers as additional barrier since the water goes from secondary treatment directly to disinfection followed by discharge. As for solids treatment, the unit processes are comparable to the base case with thickening by gravity belt thickener (GBT), anaerobic digestion, dewatering by centrifuge. The natural gas produced during anaerobic digestion will be used as an energy source for cogeneration using an engine with a jacket and exhaust heat recovery.

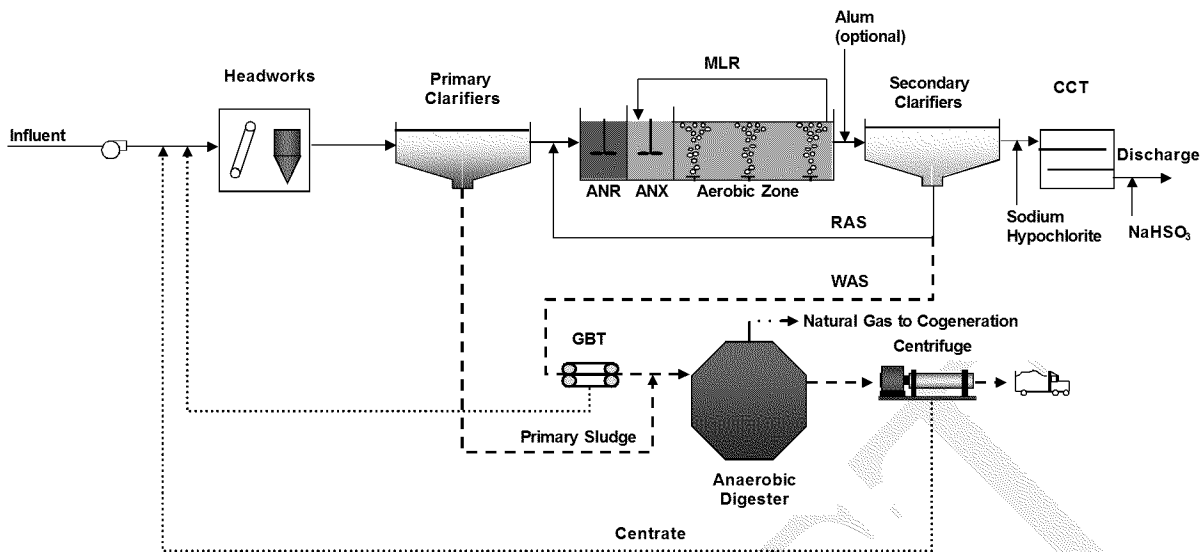


Figure 7. Level 1 Plant Schematic

4.1.3 Level 2 (4-8 mg/L N; 0.1-0.3 mg/L P)

The nutrient discharge levels are more stringent than Level 1 and as a result require additional removal mechanisms. A schematic of treatment Level 2 is shown in Figure 8. The secondary process transitions from the A2O process in Level 1 to a 4-stage Bardenpho in Level 2. Additionally, the secondary process is equipped with an optional external carbon source (e.g., methanol). Unlike Level 1, optional metal salt (e.g., alum) is located in the secondary clarifiers since there is tertiary treatment in the form of filtration. The optional metal salt is not included in the GHG calculations. Upstream of the filters is alum addition used for phosphorus precipitation prior to filtration.

As with Level 0 and 1, the solids treatment contains a GBT, anaerobic digestion, and dewatering by way of centrifuges. Also, the natural gas produced during anaerobic digestion will be used as an energy source for cogeneration using an engine with a jacket and exhaust heat recovery.

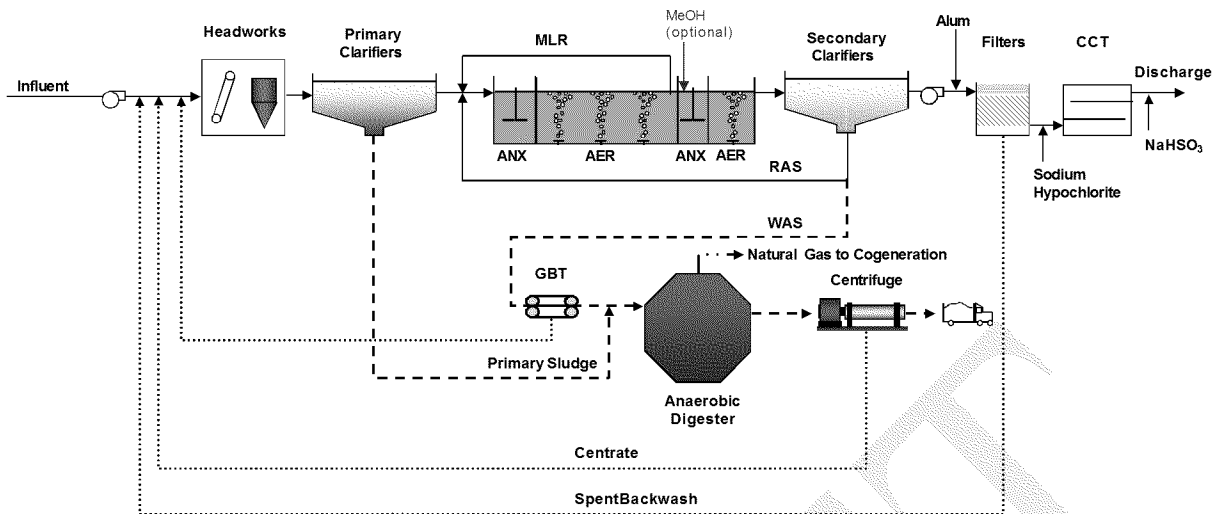


Figure 8. Level 2 Plant Schematic

4.1.4 Level 3 (3 mg/L N; <0.1 mg/L P)

The treatment facility in Level 3 is close to reaching the limit of technologies with respect to nutrient removal for both N and P. A schematic of treatment Level 3 is shown in Figure 9.

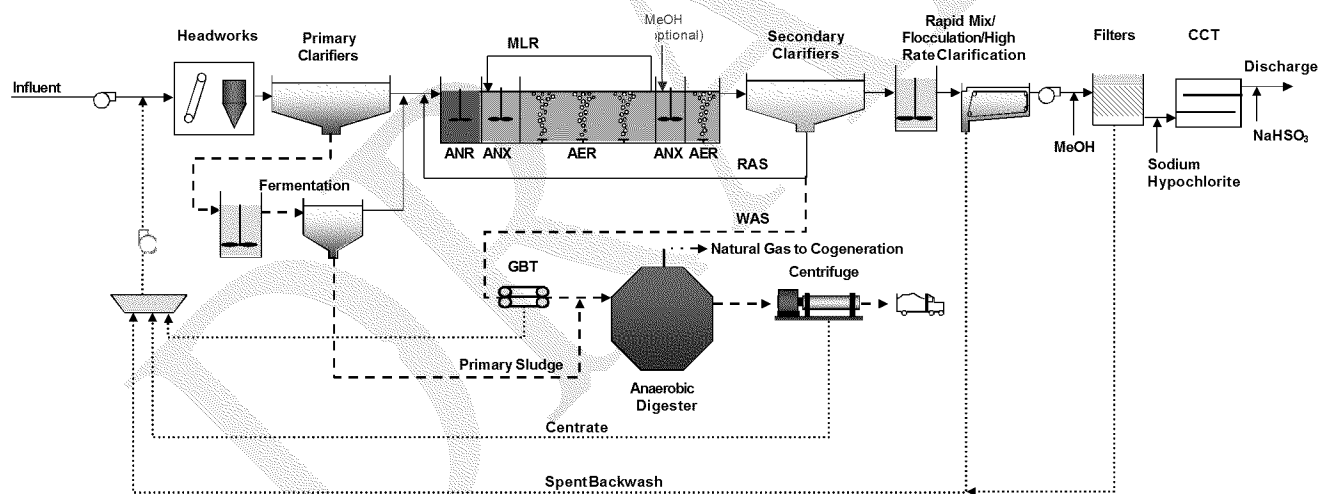


Figure 9. Level 3 Plant Schematic

For both N and P, the influent does not consistently supply adequate soluble BOD (sBOD) to fuel N and P removal. To overcome this potential inconsistency, primary solids are subjected to fermentation. The fermented primary solids produce volatile fatty acids (i.e., sBOD) that are returned to the liquid stream for the secondary process. The fermentation step requires fermentation equipment plus the plumbing and pumps associated with routing the flow. Except for the fact that methanol addition is required, the secondary process is similar to Level 2. Following secondary treatment, a high rate clarification (HRC) process is located upstream of the filters to promote the precipitation and removal of P. To ensure the removal of nitrate, the filter serves as a denitrification filter.

The solids treatment in Level 3 differs from the previous Levels. As previously mentioned, the primary solids are fermented to generate sBOD for the secondary process. Additionally, the return side streams (RSS) are equalized and slowly bleed back into the liquid stream. The equalization of RSS is critical given the fact that RSS constitutes roughly 20 percent of the overall nitrogen load on the secondary process. As with all the previous levels, the natural gas produced during anaerobic digestion will be used as an energy source for cogeneration using an engine with a jacket and exhaust heat recovery.

4.1.5 Level 4 (1 mg/L N; <0.01 mg/L P)

The most stringent permit of the five-tiered approach requires advanced tertiary treatment technologies, such as a membrane. A schematic of treatment Level 4 is shown in Figure 10. The removal strategy mimics Level 3 until the tertiary denitrification filters. Following the denitrification filters, side-stream RO is implemented to meet the stringent 1 mg/L TN-N and 0.01 mg/L TP-P. The first membrane, micro-filtration (MF), serves as pre-treatment for the second membrane step, reverse osmosis (RO). The RO is essential to meeting the permit due to the rDON/rDOP effluent levels associated with the waste stream.

The solids treatment is comparable to Level 3 with use of fermentation. As with the previous hauls, the cogeneration will utilize an engine with a jacket and exhaust heat recovery.

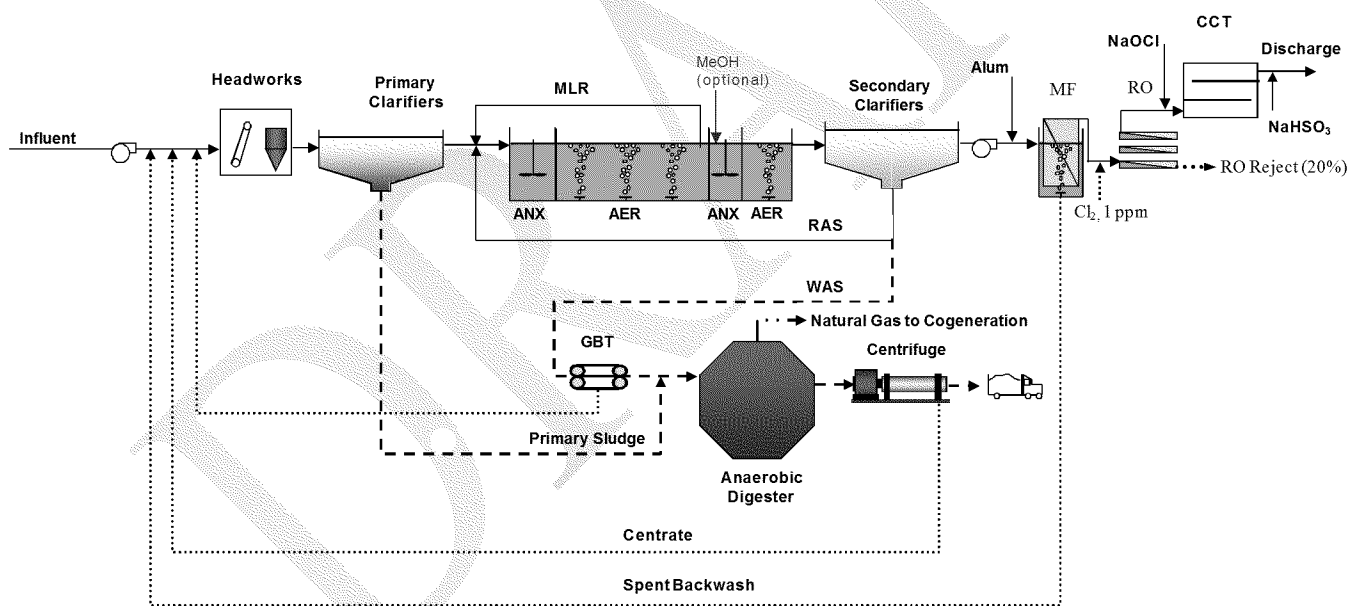


Figure 10. Level 4 Plant Schematic.

4.2 Design Criteria

Design of the steady state mass balance is based on a 10 mgd annual average flow condition. Thus, peaking factors are excluded from the calculations. However, each unit process is sized by design criteria related to annual average conditions. The liquid and solid streams design criteria are listed in Table 11 and Table 12, respectively.

Table 11. Liquids Stream Design Criteria – Based on Average Flow and Load

Process	Design Criteria
Influent Flow	10 mgd
Temperature	20°C
Primary Clarifiers	1,000 gpd/sf; 2 hr HRT
Act. Sludge	-
Level 0	Aerobic SRT = 2 d, MLSS = 1,250 mg/L, DO = 2 mg/L, Alpha = 0.30
Level 1-4	Aerobic SRT = 10 d, MLSS = 2,500 mg/L, DO = 2 mg/L, Alpha = 0.45, MLR = 3Q
Secondary Clarifiers	600 gpd/sf, 24 lb/d/sf
High Rate Clarifier	200 sf/mgd
Filtration	3 gpm/sf on average
Denitrification Filter	1.5 gpm/sf
Micro-Filtration	50 gfd
Reverse Osmosis	40 gfd
Chlorine Contact Tank	30 – 60 min HRT

Table 12. Solids Stream Design Criteria

Process	Design Criteria
Gravity Belt Thickener	275 gpm/m; 1,000 lb/hr/m
Anaerobic Digester	18 d (for Annual Average); 0.15 lb VSS/cf/d
Dewatering Centrifuges	10,000 lb/d (for Annual Average); 100 gpm (for Annual Average)
Fermentation	4 d (for Annual Average)

4.3 Greenhouse Gas Calculation Assumptions

The steady state mass balance results were used to calculate GHG emissions. The assumptions utilized to convert between energy demand, chemical demand and production, as well as biologically mediated gases and GHG emission is provided in Table 13. The assumptions are based off USEPA (2007) values for energy production, IPCC (2006) for biologically mediated GHG emissions, and various resources for chemical production and hauling from production to the wastewater facility. Additionally, the natural gas produced during anaerobic digestion that is utilized as a fuel source is converted to energy by way of MOP8 (2009) recommended waste to energy values.

Table 13. Greenhouse Gas Production Assumptions

Parameters	Units	Value	Source
N ₂ O to CO ₂ Conversion	lb CO ₂ /lb N ₂ O	296	IPCC, 2006
CH ₄ to CO ₂ Conversion	lb CO ₂ /lb CH ₄	23	IPCC, 2006
Energy Production			
CO ₂	lb CO ₂ /MWh	1,329	USEPA (2007)
N ₂ O	lb N ₂ O/GWh	20.6	USEPA (2007)

Parameters	Units	Value	Source
CH ₄	lb CO ₂ /GWh	27.3	USEPA (2007)
Sum Energy Production	lb CO ₂ /MWh	1336	USEPA (2007)
GHGs per BTU Natural Gas			
CO ₂	lb CO ₂ /MMBTU Natural Gas	52.9	California Climate Action Registry Online Reporting Tool
N ₂ O	lb N ₂ O/MMBTU Natural Gas	0.0001	California Climate Action Registry Online Reporting Tool
CH ₄	lb CO ₂ /MMBTU Natural Gas	0.0059	California Climate Action Registry Online Reporting Tool
Sum Natural Gas		53.1	California Climate Action Registry Online Reporting Tool
Biogas Purity	% Methane	65	WEF, 2009
Biogas to Energy	BTU/cf CH ₄	550	WEF, 2009
Digester Gas to Electrical Energy Transfer Efficiency	%	32	HDR Data
Chemical Production			
Alum	lb CO ₂ /lb Alum	0.28	SimaPro 6.0 - BUVAL250, Eco- indicator 95
Alkalinity	lb CO ₂ /lb Alkalinity	0.35	SimaPro 6.0 - BUVAL250, Eco- indicator 95
Polymer	lb CO ₂ /lb Polymer	1.18	Owen (1982)
Methanol	lb CO ₂ /lb Methanol	0.67	Willis et al., (2009)
Soda Ash	lb CO ₂ /lb Soda Ash	0.42	Assumes Trona Ore used; IPCC, 2006
Sodium Bisulfite	lb CO ₂ /lb Sodium Bisulfite	0.25	Biswas (2009)
Sodium Hypochlorite	lb CO ₂ /lb Sodium Hypochlorite	1.07	Owen (1982)
Hauling Distance		-	
Local	miles	100	-
Regional	miles	750	-
National	miles	2000	-
Hauling Emissions			
CO ₂	kg CO ₂ /gal diesel	10.2	California Climate Action Registry Online Reporting Tool
N ₂ O	kg N ₂ O/gal diesel	0.0001	California Climate Action Registry Online Reporting Tool
CH ₄	kg CH ₄ /gal diesel	0.003	California Climate Action Registry Online Reporting Tool
Sum Hauling Fuel	kg CO ₂ /gal diesel	10.2	California Climate Action Registry Online Reporting Tool

Emission factors for sodium bisulfite are not readily available in the literature. Rather than leaving the chemical blank, we borrowed the approach implemented by Biswas (2009). Biswas accounted for sodium bisulfite by adding the emission factors for the two primary ingredients (i.e., caustic soda and sulfur dioxide) to determine the corresponding emission factor. It is important to recognize that the true emission factor for sodium bisulfite will be higher since the weighted emission factors used do not reflect the energy associated with combining the two.

4.4 System Inputs

A summary of the system inputs are summarized in Table 14 with a corresponding plot in Figure 182. It is important to recognize that the evaluation considers GHG emissions outside the boundary of a municipality. For example, both the biosolids and chemical hauling are including in the GHG calculations. Additionally, GHG emissions associated with each chemical used in treatment is incorporated in the calculations. Although the GHG calculation includes emissions generated during chemical production, the GHGs produced during the exploration of chemicals are not included in the calculation.

Table 14. System Inputs and Assumptions for this Investigation.

GHG scope	GHG Contributor	Addressed in this investigation	Reference/value/comment
1	Carbon dioxide and other GHG produced from cogeneration	Not considered	Biogenic carbon; Contributors outside cogeneration are small
1	Carbon Dioxide produced in wastewater treatment	Not considered	Biogenic carbon
1	Fugitive methane from anaerobic processes	Considered in calculation	Relatively small and considered for all conditions investigated. Default value from climate registry only considers septic tank and wetlands/lagoons.
1	Nitrous oxide discharged to the air and effluent	Considered in calculation	Considerable research now being done on Nitrous oxide emissions (e.g., Yu et al., in press). Default value from IPCC (2006)
1	Natural gas for backup digester heating, building heating as well as other fuels used in the plant	Considered in calculation	
1	Reuse of biogas on site in boilers and cogeneration	Not considered	Biogenic carbon
2	Purchased electricity	Considered in calculation	
3	Manufacturing and hauling of chemicals	Considered in calculation	Coagulants, flocculants, methanol and other chemicals related to nutrient removal
3	Biosolids haul	Considered in calculation	Fuel for trucking. Offsite GHG for reuse or disposal not included. Hauling included according to Climate Change Protocol.
3	Brine management from reverse osmosis	Considered in calculation	Treatment alternatives are wide that ranges from sewer discharge to advanced thermal evaporation. We used deep well injection.

GHG scope	GHG Contributor	Addressed in this investigation	Reference/value/comment
3	Methane in Raw Sewage	Not considered	May be a significant contributor to GHG in WWTPs but is not considered constant for all nutrient levels of treatment

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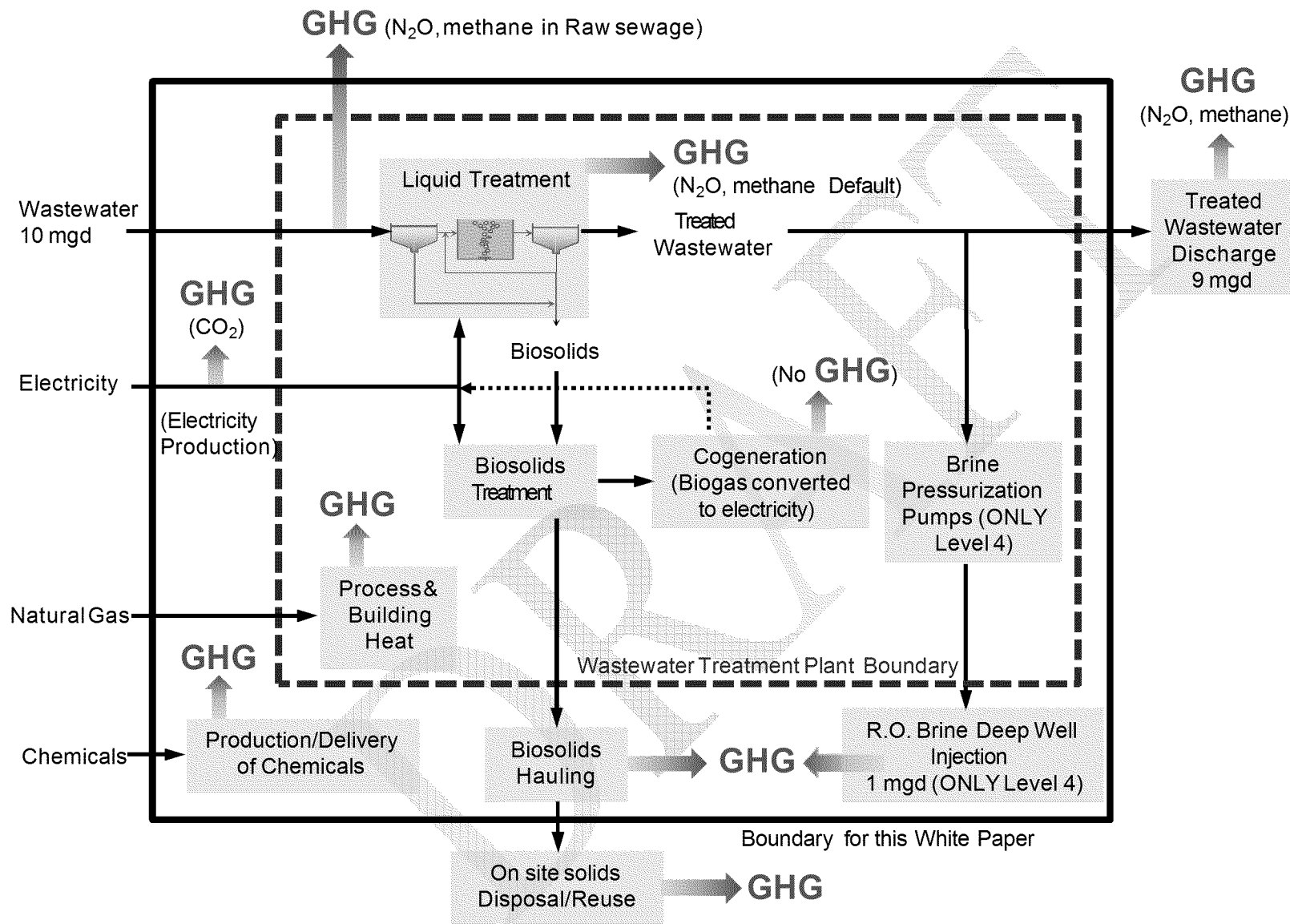


Figure 11. Mass Balance System Inputs

CHAPTER 5.0 - SUSTAINABILITY CONSEQUENCES FOR FIVE TIERED LEVELS OF TREATMENT

5.1 Steady State Mass Balance Results

A detailed breakdown of the GHG emissions of each level per unit process is provided in Table 15. The transition from a cBOD mode facility (Level 0) to nutrient removal translates to a roughly doubling of GHG emissions for Level 1 (1600 versus 3300 CO₂ equivalents metric tons/yr). There is an increase in GHG emissions of roughly 400 and 800 CO₂ equivalents metric tons/yr from Levels 1 to 2 and Levels 2 to 3, respectively. And finally, the GHG emissions for Level 4 reveal a more than doubling effect from Level 3 to Level 4. The sharp increase from Level 3 to 4 is largely based on energy demand associated with MF and RO tertiary treatment plus the energy associated with deep well injection pumping.

Table 15. Greenhouse Gas Emission Results

Treatment	Level 0 No N/P Removal (CO ₂ eq metric tons/yr)	Level 1 8 mg/L N 1 mg/L P (CO ₂ eq metric tons/yr)	Level 2 4-8 mg/L N 0.1-0.3 mg/L P (CO ₂ eq metric tons/yr)	Level 3 3 mg/L N <0.1 mg/L P (CO ₂ eq metric tons/yr)	Level 4 1 mg/L N <0.01 mg/L P (CO ₂ eq metric tons/yr)
Sub-Total Pri.	238	238	238	238	238
Sub-Total Act. Sludge	1,471	2,605	2,844	2,836	2,836
Sub-Total Tertiary	203	487	652	1,354	6,826
Sub-Total Liquid Stream	1,913	3,331	3,735	4,428	9,900
Sub-Total Solids	-294	-56	-91	19	19
Total	1,619	3,274	3,643	4,447	9,919

Figure 12 to Figure 14 take the values from Table 15 and present the values as liquid stream GHG emissions (Figure 12), the solids stream GHG emissions (Figure 13), and the combined GHG emissions (Figure 14).

The liquid stream values reveal a roughly doubling of the GHG emissions from Level 0 to Level 1. This is largely attributed to the additional aeration required for nitrification and MLR pumping. The increase from Level 1 to Level 2 is a result of the need to filter. The use of fermentation provides savings in Level 3, but the savings are off-set by the use of high rate clarification that requires more alum and polymer. And finally, the MF and RO advanced tertiary treatment system requires such elevated pumping levels for treatment and brine management that the GHG emissions more than double while transitioning from Level 3 to 4. It is important to note that the doubling of GHG emissions from Level 3 to 4 only remove two additional mg/L as nitrogen (160 lb/d nitrogen for a 10 mgd flow).

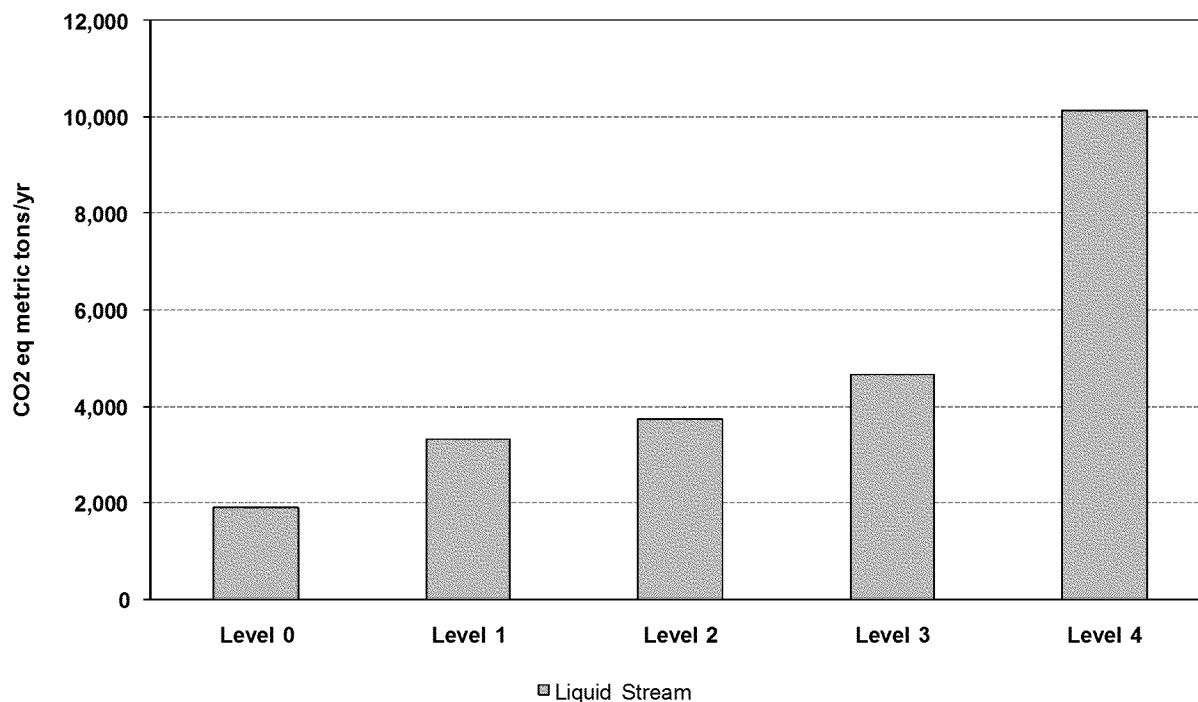


Figure 12. Liquid Stream Mass Balance GHG Results

For all cases, the solids stream (Figure 13) is an energy resource due to the use of natural gas produced during anaerobic digestion. The lower aerobic SRT associated with Level 0 has a higher yield than Levels 1 to 4. As a result, more solids are sent to the digester which translates to more natural gas production.

The difference in Levels 1 to 4 relates to chemical usage variability and the use of fermentation in Level 3. The fermentation step sends the sBOD substrate to the secondary process rather than using it to fuel anaerobic digestion. Thus, the amount of produced natural gas is reduced for Level 3 in the anaerobic digester.

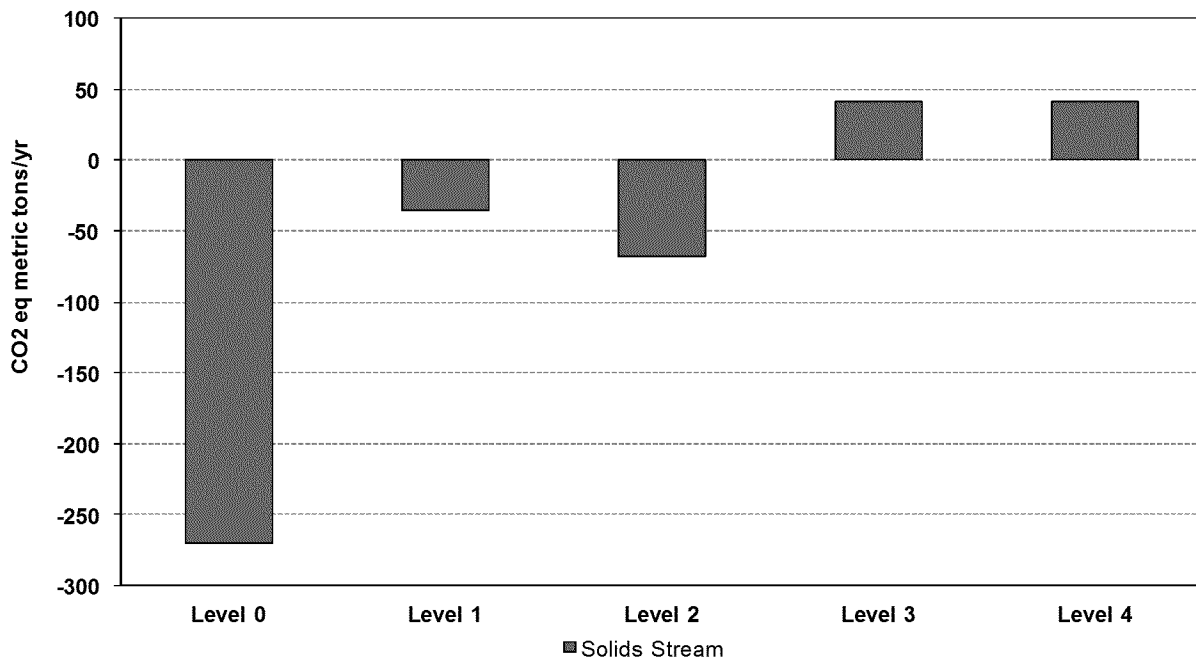


Figure 13. Solids Stream Mass Balance GHG Results

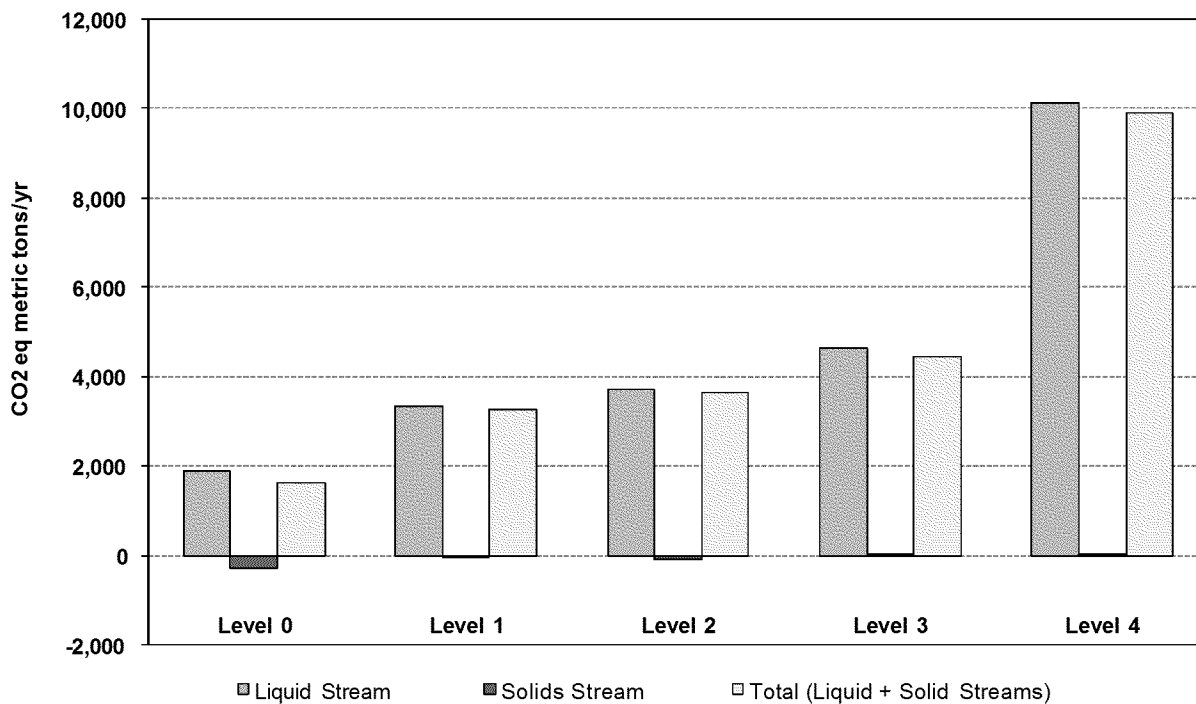


Figure 14. Combined Liquid and Solids Stream Mass Balance GHG Results

5.2 GHG Emissions Distribution per Treatment Level

For each level, the distribution of GHGs per treatment level was considered as shown in Figure 15. The overall CO₂ equivalent metric tons per year replicate those ‘Total’ values in Figure 14.

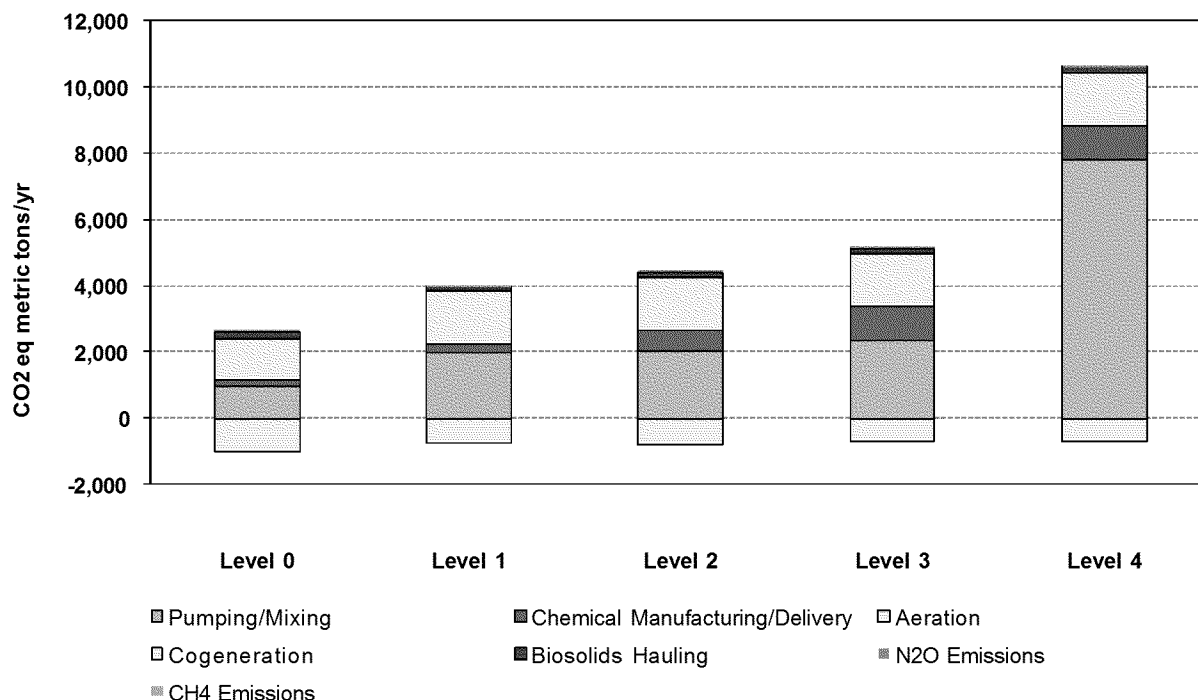


Figure 15. GHG Emissions Distribution per Treatment Level

The two largest contributors to GHGs are ‘Aeration’ and ‘Pumping/Mixing’. The Cogeneration values are largest for Level 0 since the WAS associated with a 2-d SRT over the 8-d aerobic SRT associated with Levels 1-4 generates more methane. In contrast, methane and nitrous oxide result in the least amount of GHG emissions. It is important to re-state that the IPCC (2006) method for calculating methane and nitrous oxide emissions was utilized.

The hauling associated with biosolids and chemical delivery is based on local delivery (i.e., 100 miles). The impact of chemical production was not apparent until Levels 2 to 4. In particular, Levels 3/4 have high rate clarification and tertiary denitrification which elevates the impact of chemicals on the overall distribution. As for Level 2, the elevated impact of chemical production relates to the required use of methanol to serve as substrate in the secondary process and alum for filtration.

5.3 Sustainability Impacts of Incremental Increase in Nutrient Removal from the Various Levels

The incremental GHG emission increase per additional nutrient load removal as you go from one level to the next was calculated on a per constituent basis for both N and P. Figure 16 and Figure 17 show the plots for N and P, respectively. To differentiate between N and P, additional wastewater equipment required to remove the constituent was penalized. For example, the MeOH addition and additional aeration requirements associated with Level 1 to

Level 4 is due to nitrogen removal. In contrast, the alum/polymer addition plus the addition of filters is for phosphorus removal. As for Level 4, meeting the 1 mg/L as N and <0.01 mg/L as P both require side-stream RO treatment. Thus, the impact of RO was considered for both N and P removal.

The transition from Level 0 to 1 revealed a roughly doubling of GHG emissions for N since you need over one incremental GHG increase. The Level 1 to 2 shows comparable findings to Level 0 to 1. There is an increase of roughly 3 from Level 2 to 3. This increase is attributed to the tertiary denitrification plus the use of fermentation. A tertiary denitrification filter requires more surface area, whereas as the primary solids that contribute to methane production is sacrificed as substrate for the activated sludge. And finally, the transition from Level 3 to 4 has an increase greater than 30 times due to the addition of side-stream RO coupled with the energy demand of DWI. Based on the incremental GHG increase per additional lb N removed, the point of diminishing returns appears from Level 2 to 3 as the increase is 3 times greater GHG emissions.

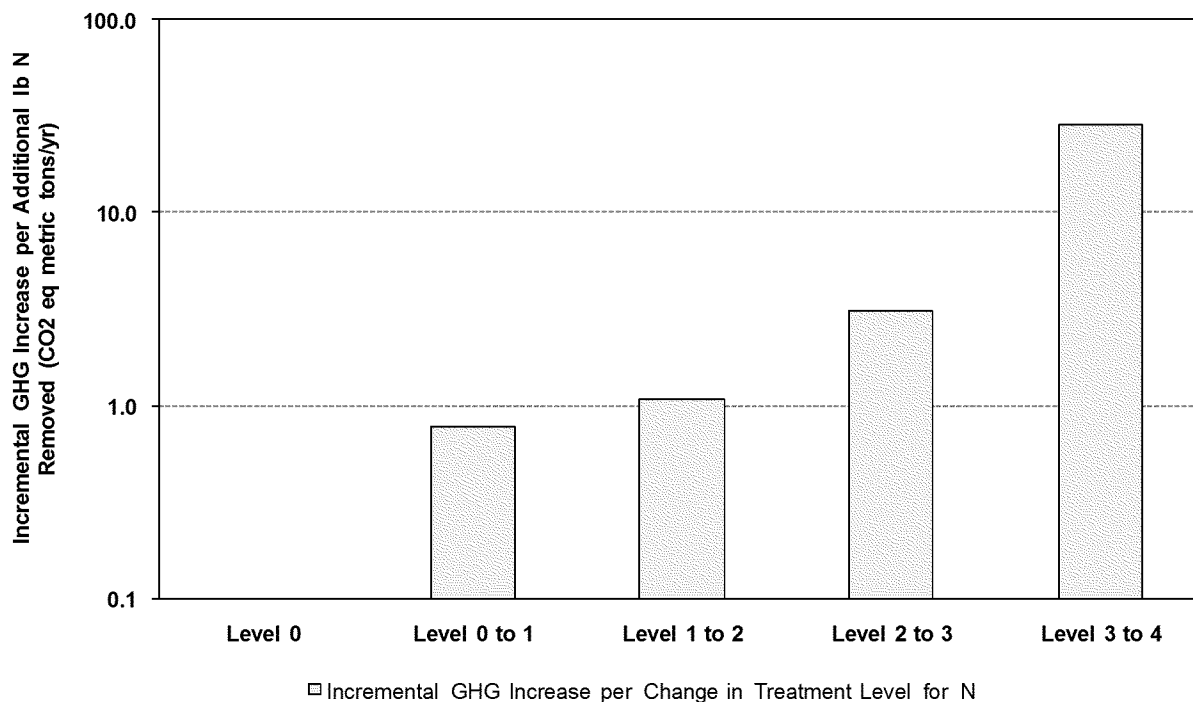


Figure 16. Incremental GHG Increase per Additional lb N Removed

The incremental GHG increase per additional P load removal plot in Figure 17 is comparable to findings in Figure 16. The values roughly double from Level 0 to 1, followed by a comparable increase from Level 1 to 2. The increase in incremental GHG from Level 2 to 3 is more pronounced for P than N as evidenced by the roughly 35 times increase. And finally, the increase in incremental GHG from Level 3 to 4 approaches 600 times increase for P. As with incremental GHG increase per additional N load removal, the P load removal reveals that a point of diminishing returns is reached as you transition from Level 2 to 3.

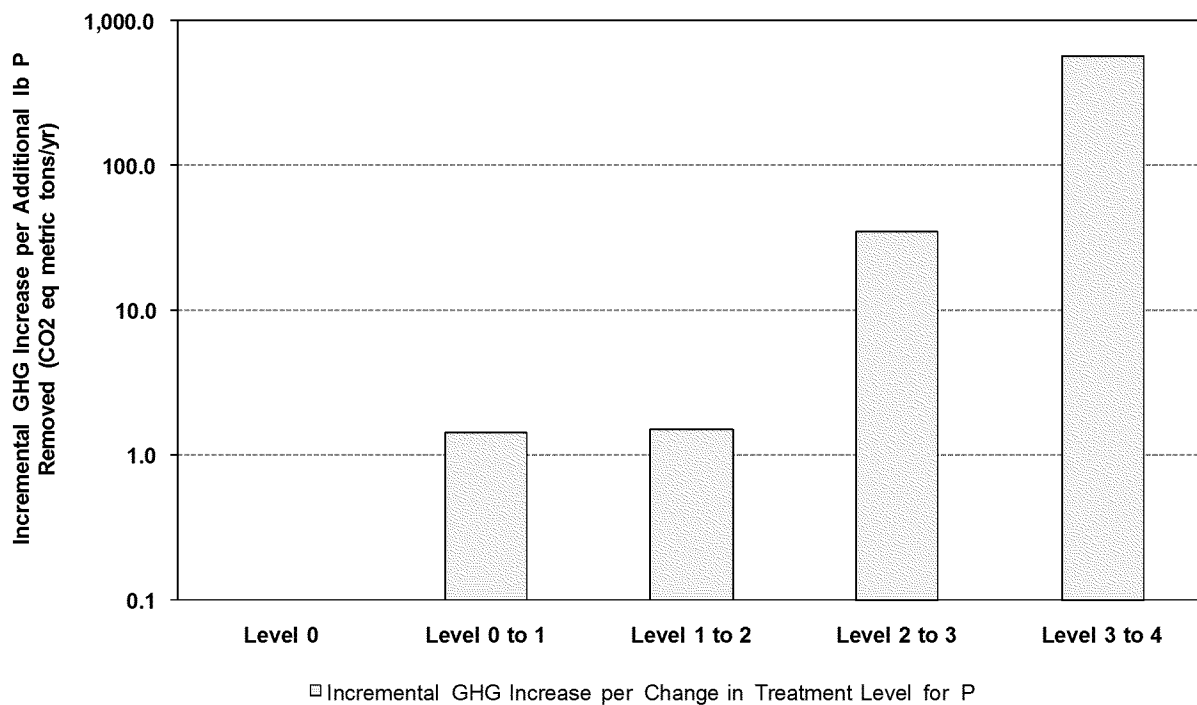


Figure 17. Incremental GHG Increase per Additional lb P Removed

5.4 Algal Production Potential on Receiving Water Bodies

Up to this point, the results section has focused solely on GHG emissions associated with each treatment level. In contrast to GHGs, the receiving water bodies are positively impacted by a higher water quality discharge with higher treatment level. The improved water quality associated with a higher treatment level can be evaluated by considering algae production potential per treatment level. The algae production associated with each treatment level was calculated based on nutrient discharge loads. It was assumed that for every 100 lb of algae produced requires 10 lb of N and 1 lb P. The plot of GHG emissions along with algae production per treatment level is shown in Figure 18. A point of diminishing return is reached in algae production from Level 2 to 3 as evidenced by the 1,200 to 800 lb/d algae production, respectively.

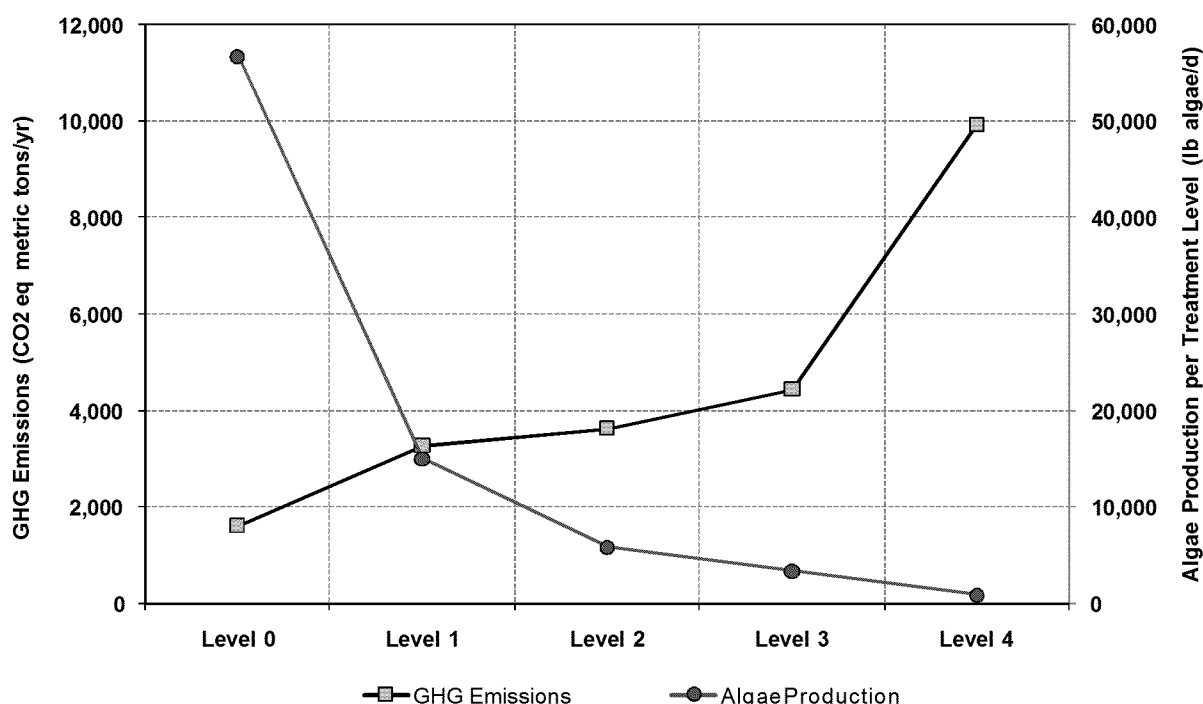


Figure 18. GHG Emissions and Algae Production per Treatment Level.

5.5 Transportation Sustainability Impacts for Chemicals

The role of hauling from three different travel distances was considered based on the mileage shown in Table 13. Per treatment level, delta values were developed for variable chemical hauling distances as shown in Table 16. The decision to use chemicals from a regional supplier over a local supplier can impact facilities GHG emissions by as much as 5 percent (Level 2). This percentage increases to upwards of 15 percent (Level 3) as the switch is made from local (100 miles) to national (1,500 miles) hauling of chemicals.

Table 16. Greenhouse Gas Emission Deltas for Variable Biosolids and Chemical Hauling Requirements

Treatment	Units	Level 0	Level 1	Level 2	Level 3	Level 4
		No N/P Removal	8 mg/L N 1 mg/L P	4-8 mg/L N 0.1-0.3 mg/L P	3 mg/L N <0.1 mg/L P	1 mg/L N <0.01 mg/L P
Base Hauling Local (100 miles)	CO ₂ equivalents (metric tons CO ₂ /yr)	1619	3274	3643	4447	9919
Chemical Hauling Regional (500 miles)	CO ₂ equivalents (metric tons CO ₂ /yr)	43 (3%)	43 (1%)	164 (5%)	224 (5%)	218 (2%)
Chemical Hauling National (1500 miles)	CO ₂ equivalents (metric tons CO ₂ /yr)	124 (8%)	124 (4%)	478 (13%)	655 (15%)	637 (6%)

Notes:

The value in parentheses is the percent increase in GHG emissions associated with the biosolids and chemical hauling

5.6 Costs per Treatment Level

The capital and operations cost per treatment level are provided in Table 17. For the capital costs, the switch from a carbonaceous BOD mode facility in Level 0 to a nutrient removal facility requires roughly twice as much capital. This can be attributed to an increase in square footage for the secondary process (i.e., activated sludge plus secondary clarifiers). The costs for Levels 1 to 3 are all within 10 percent of each other. The transition from Level 3 to 4 requires an additional 50 percent increase in capital as a result of the side-stream MF/RO equipment. It is important to note that land costs are not included in the capital cost calculations.

Table 17. Capital and Operations and Maintenance Costs for Each Level

Level	Capital Costs (\$/gpd)	Capital Costs for 10 mgd (Million \$)	Operations Cost (\$/MG Treated) *	Operations Cost (\$1,000/yr/10 MG Treated) *
0 (No N/P Removal)	7.3	73	191	696
1 (8 mg/L N; 1 mg/L P)	12.5	125	335	1,222
2 (4-8 mg/L N; 0.1-0.3 mg/L P)	13.3	133	510	1,861
3 (3 mg/L N; <0.1 mg/L P)	13.8	138	690	2,517
4 (1 mg/L N; <0.01 mg/L P)	20.0	200	1,183	4,319 **

Notes:

* Operations cost = energy and chemical cost. Labor and maintenance costs are excluded

** Does not include membrane replacement costs as this is highly dependent on membrane material and operating conditions. MF/RO replacement costs estimated to be \$240,000/yr for a 10-yr life-span

The capital costs include construction, engineering and administration costs. Base construction calculations were based on past experience. The estimates were built process by process with a 25% adder for “undefined structures”, an additional 28% adder for site work, yard piping soil conditions, electrical power supply and site electrical. Contractor costs of 25 % were added for field general conditions, mobilization, demobilization sales tax, overhead and profit and bonds/insurance. A grand total for construction was calculated and a 20% construction contingency was added. Additional “soft” costs of 28% were added to the construction grand total for planning and design engineering, construction engineering and management, legal and owner administration.

As for operations, there is a wider range of values than for capital. Labor and maintenance activities are not included. There is a steady increase in operations between each treatment level with a minimum increase of approximately 50 percent (Level 2 to 3). The largest increase in operations cost from both a percentage and cost perspective occurs from Level 3 to 4 (nearly 100 percent increase). The value is essentially 100 percent since the value in Table 17 does not include MF/RO replacement, which equates to \$240,000 per year for replacement every 10 years.

To better understand the relationship between nutrients removed and cost, the incremental increase in cost per additional N/P removal values were developed as shown in Figure 19 and Figure 20, respectively. As with the incremental GHG increase per additional N/P removal (Figure 16 and Figure 17), the values discriminate between N and P by penalizing the costs required to remove each constituent. The use of MF/RO is required to meet the treatment objectives for both N and P.

The operational cost for N removal increases steadily from Levels 0 to 3. In particular, the cost increases more than three fold per additional N load removed from Level 1 to 2.

Following Level 3, the increase in cost to Level 4 is a four fold increase with respect to Level 3 (\$7 to 26). In contrast to N, the incremental operations cost for P removal is less pronounced up to Level 2. The transition from Level 2 to 3 reveals a ten fold increase from \$7 to \$78 per additional P load removed. The increase from Level 3 to 4 is a smaller increase from a fraction perspective (seven fold), but the cost increase is the most pronounced with an increase from \$78 to \$504.

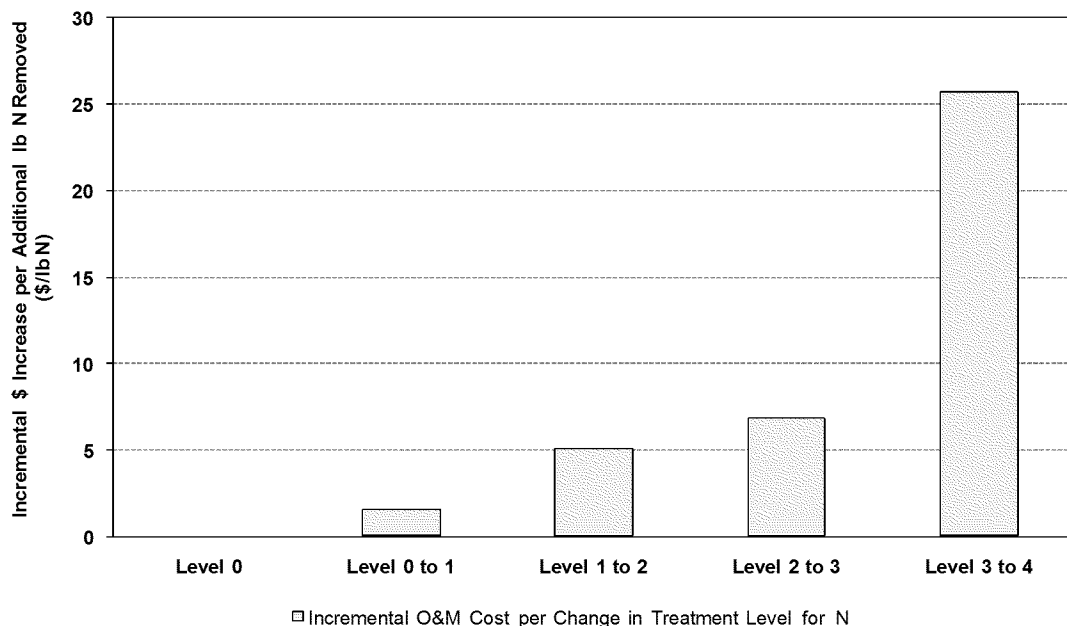


Figure 19. Incremental Operations Cost Increase per Additional N Load Removed.

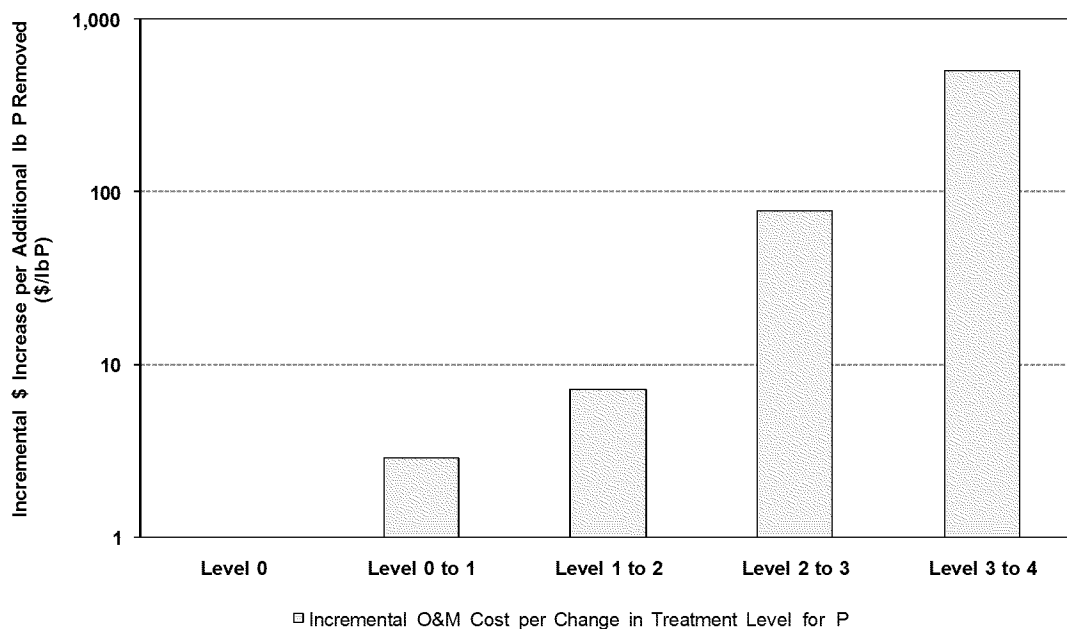


Figure 20. Incremental Operations Cost Increase per Additional P Load Removed.

5.7 Discussion

5.7.1 Capital Cost

The capital costs illustrate (Table 17) that the transition from a cBOD mode of Level 1 to nutrient removal requires a roughly doubling of capital costs for Levels 1 to 3. For the case of Level 4, the capital cost is essential three times larger than Level 0. The additional costs are a direct result of additional secondary treatment acreage, chemical storage facilities, filtration equipment, fermentation for Levels 3/4, high rate clarification for Levels 3/4, plus side-stream RO and DWI in the case of Level 4. The capital costs do not include land requirements that will add an additional cost for Levels 1 to 4.

Despite the White Paper's emphasis on GHG emissions at WWTPs, the GHGs associated with construction were not included in the evaluation. Those costs would include GHGs from materials, hauling, and earthmoving equipment. The GHGs associated with construction materials and actual construction practices are assumed to be relatively small in comparison to operations over the life-span.

5.7.2 Operations Cost per Treatment Level

The operations costs provided in Table 17 provided a lump sum of annual operations cost. The addition of metal salt (alum or ferric) is required starting in Level 2 (TN = 4 – 8 mg/L as N, TP = 0.1 – 0.3 mg/L as P). For Levels 2 to 3, the distribution of operations cost between energy and chemicals are based on treatment process (i.e., secondary or tertiary treatment). For example, secondary process operations costs are governed by energy in Level 2 and 3. The additional energy demands from pumping, mixing, and aeration requirements in the secondary process requires 65 percent of the secondary treatment costs versus 35 percent for chemicals manufacturing/hauling. In contrast, the chemicals associated with tertiary treatment for Levels 2 and 3 require 57 and 70 percent, respectively, of the tertiary treatment costs. Once the treatment requires Level 4, the annual cost essentially doubles. The sharp increase in operations cost is a direct result of RO and DWI. In both cases, RO and DWI costs are solely from energy costs due to the required pressures (215 and 430 psi, respectively).

5.7.3 Incremental GHG Increase per Treatment Level

The incremental GHG increase per change in treatment level while removing nitrogen (Figure 16) or phosphorus (Figure 17) revealed that a point of diminishing returns is reached for both nitrogen and phosphorus. In the case of nitrogen, the incremental GHG increase goes from a roughly one-fold increase from Level 0 □ 1 □ 2 to a three-fold increase from Level 2 to 3. From Level 2 to 3, the discharge concentration reduces from on average 6 to 3 mg/L nitrogen (240 lb/d N). Moving beyond Level 2 treatment results is potentially impractical since only increases in GHG to achieve relatively small removals of nitrogen. The incremental GHG values for phosphorus (Figure 17) are even more pronounced than for nitrogen. As with nitrogen, the increase in GHG emissions reaches potentially impractical values following Level 2. Moving beyond Level 2 results in huge GHG increases for a relatively small removal of phosphorus (<9 lb/d phosphorus from Level 2 to 3).

The fact that the incremental GHG increases reach monumental levels for Levels 3 and 4, regulators permitting extremely sensitive water bodies requiring such treatment should consider alternative strategies. For example, a combination of Level 2 treatment objectives combined

with best manage practices for non-point source loads might be a more viable approach at meeting the overall load targets on the sensitive receiving water body.

The algae production plot (Figure 18) further supports the notion that relatively small nutrient load savings are achieved from Level 2 □ 3 □ 4. A point of diminishing returns is apparent following Level 2 with respect to algae production.

5.7.4 Which Parameter is Governing GHG Emissions?

For all treatment levels, energy dominates the overall sustainability impacts in terms of GHG emissions within the wastewater facility. For Level 0, energy represents 60 percent of the total CO₂ equivalents if IPCC (2006) default values of methane and nitrous oxide are used in calculations. For Level 4, energy represents 79 percent of the total CO₂ equivalents. Emissions of methane (23 times more potent than CO₂) from raw sewage might be significant as indicated earlier in this document which in turn would reduce the GHG proportion load from energy. Likewise, nitrous oxide (296 times more potent than CO₂), is produced in raw sewage and in treatment plants. Quantification of nitrous oxide production in treatment plants is a relatively new endeavor and researchers have shown that nitrous oxide emissions in the plant as well as leaving the plant in the effluent may have a significant impact on sustainability. For now, energy appears to be the biggest contributor with nitrous oxide and methane possibly contributing much more than the default values now used by the IPCC (2006).

The fact that energy demand is the primary culprit in GHG emissions is in agreement with Keller and Hartley (2003) where they compared a municipality with anaerobic treatment at the front-end of the facility versus the layout of Level 0 (Figure 6). They found a municipality based on front-end anaerobic treatment required 1.0 kg CO₂/kg COD_{removed} versus 2.4 kg CO₂/kg COD_{removed} for a cBOD plant (Level 0). They attributed the 240 percent increase for the cBOD facility on the additional energy required for pumping, mixing, and aeration. Tripathi (2007) also considered different types of municipalities: 1) a drinking water plant, 2) a WWTP, and 3) a WWTP with reclamation. For all three facilities, energy demand was the primary contributor to GHGs that ranged from 44 to 91 percent of the GHGs. A third study by Racoviceanu et al. (2007) considered energy demand for a drinking water municipality, from which on-site pumping alone represented 90 percent of GHG emissions.

It is clear from our findings plus the literature that energy appears to be the largest contributor to GHGs from WWTPs. Strategies to reduce this demand consists of i) adjustment in treatment plant configuration as suggested by Keller and Hartley (2003), ii) more efficient on-site pumping/aeration/mixing equipment, or iii) a reduction in wastewater source load.

5.7.5 Dissolved Organic Nitrogen

As previously acknowledged in Section 2.6.2, refractory dissolved organic nitrogen (rDON) is the limiting factor in achieving low N objectives (N < 3 mg/L). DON removal in wastewater suffers from a matrix effect that impairs a facilities ability to remove rDON (Lee and Westerhoff, 2005). A collection of rDON effluent distribution concentrations have been compiled as shown in Figure 21 and Figure 22. The former plot (Figure 21) is based on a compilation of rDON effluent values nationwide, with particular emphasis on the Chesapeake Bay and Florida. The 50th percentile value is 1.2 mg/L as N, which suggests that more than half the facilities cannot reliably meet the 1 mg/L as N objective of Level 4. The latter plot (Figure 22), focuses on Maryland and Virginia municipalities that discharge to the Chesapeake Bay. Over 65 percent of the municipalities have rDON discharge values of less than 1 mg/L. These 2

plots illustrate the variability of rDON discharge values which can directly impact a municipality's ability to reliably meet stringent discharge values. Effluent limits that require nitrogen values of 2 mg/l or less could dictate the use of expensive and energy intensive (read GHG) reverse osmosis to achieve compliance.

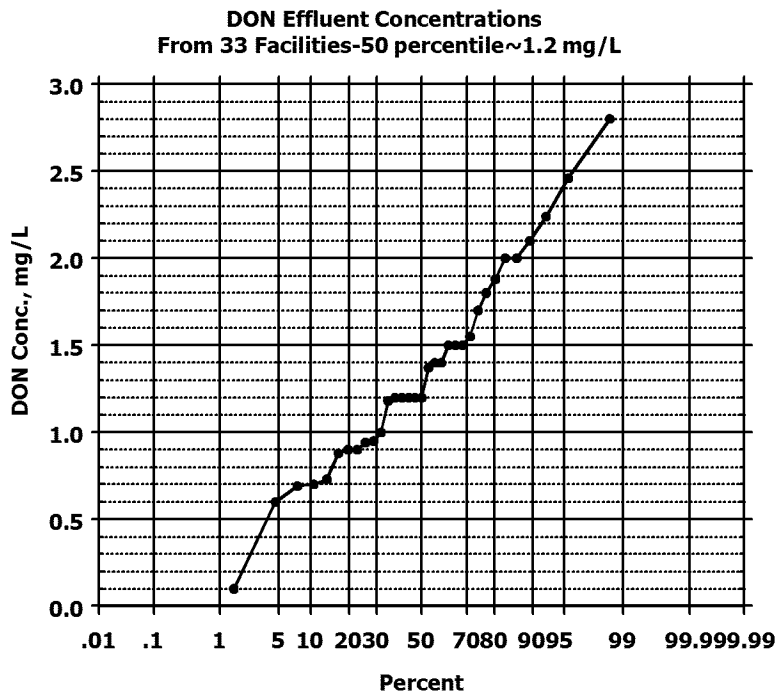


Figure 21. rDON Effluent Concentrations from 33 Facilities (Stensel et al., 2008)

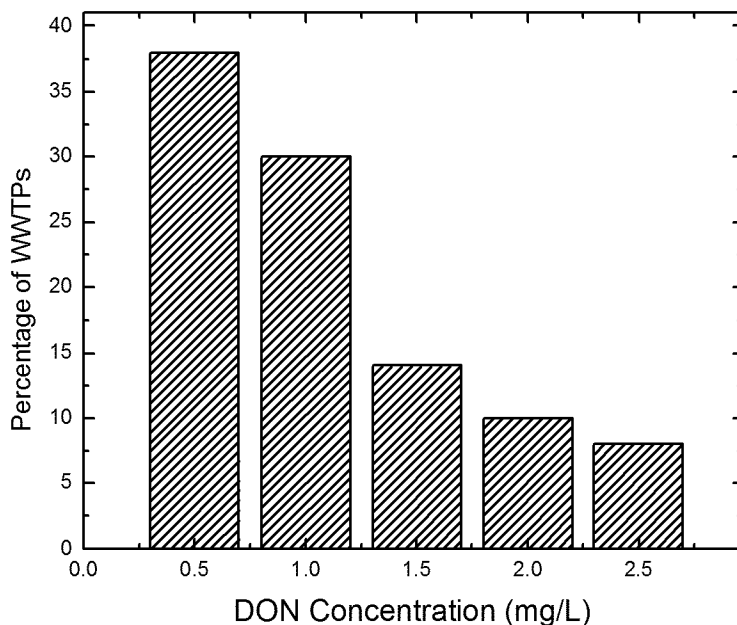


Figure 22. rDON Distribution in Maryland and Virginia (Pagilla, 2006)

With regard to nutrient removal permitting, the primary issues with rDON relates to bioavailability and whether or not to exclude from the discharge TN. DON exiting a plant comprises both refractory and labile DON. The recalcitrance of DON over a 2 week study at the Truckee Meadows Water Reclamation Facility was assessed by Pehlivanoglu and Sedlak (2004). They found that alga by itself took up 10% of the effluent DON in the absence of bacteria, whereas alga combined with bacteria facilitated a 60% removal of effluent DON. A symbiotic relationship appears to exist, whereby bacteria initiate the DON breakdown provided by alga. Their findings suggest that effluent DON can contribute to eutrophication. This is especially the case for Truckee Meadows, where DON accounts for ~85% of discharged TN.

In terms of rDON removal strategies, biological removal within the secondary process is still largely unknown. The DON entering is typically larger (MW) than effluent. Roughly 50% of the soluble DON can be removed through adsorption, such as GAC (Keller et al., 1978; Gur-Reznik et al., 2008). It is anticipated that effluent DON contains elevated levels of colloidal amino sugars (from cell walls; DCAA) (Esparza-Soto et al., 2003; Westerhoff & Esparza-Soto, 2003). Being colloidal, one would expect that it can be removed by chemical coagulation, followed by filtration and/or sedimentation. Randtke and McCarty (1979) considered lime, ferric, alum, and others and found Ferric>Lime>Alum with a range of 28 to 40% DON removal.

Advanced oxidation processes (AOP) represent another potential removal technology. Dwyer et al. (2008a,b) investigated the viability of the AOP process, UV/H₂O₂, at rDON removal. To remove roughly 25% of the rDON requires the exorbitant H₂O₂ concentration of ~3,000 mg/L.

5.7.6 Dissolved Organic Phosphorus Removal

Research on TP removal is lacking in comparison with TN. The lack of knowledge on TP removal relates to the fact that P permits have historically not been as difficult to achieve from a treatment perspective. As the permits become more stringent, research will need to better characterize the P fractions so that engineers can better design removal strategies. As with nitrogen, the fraction becomes increasingly important for meeting the treatment objectives for Level 4. Although RO can reliably meet the Level 4 phosphorus objective (< 0.01 mg/L), the incremental GHG increase for the additional 0.01 mg/L phosphorus removed is on the order of 560 times greater than Level 3.

Recent research is advancing our understanding on both P fractions and their removal mechanisms. For example, Liu et al. (2010) considered P removal based on the various fractions in BNRs. The results suggest that BNRs effectively remove most TP fractions, with higher removal efficiencies (>93%) towards bioavailable P forms that included soluble reactive P (sRP), particular reactive P portion (pRP) and particular acid hydrolysable P (pAHP). In contrast, the organic P forms had lower removal efficiency (78%). The fraction least effectively removed was soluble acid hydrolysable P (sAHP) (<40%). Chemical P removal process was more effective for elimination of sRP, sAHP and pOP, but was not as effective for removing pAHP and, it exhibited nearly no removal of dissolved organic P (DOP).

As the research better understands the fractions and mechanisms associated with removal, an opportunity might arise to meet treatment Level 4 without the use of RO and subsequently reduce GHG emissions to that of Level 3 and improve water quality.

5.7.7 Nitrous Oxide Emissions

The generation of nitrous oxide at WWTPs is thought to occur within the secondary process. Based on ongoing studies at full-scale as part of the Water Environment Research Foundation (WERF) project U4R07, inefficient nitrification and denitrification have been implicated as the main factors leading to N_2O emissions from both BNR and non-BNR processes Ahn et al. (2009). This discussion is broken up into a municipality operating under cBOD mode (Level 0) and Levels 1-4 that perform nutrient removal. A detailed description for all five treatment levels can be found in Appendix B.

WWTPs operated under cBOD mode have the ability to potentially nitrify part or all of their influent total Kjeldahl nitrogen (TKN) load at high temperatures (e.g., during summer). Under such circumstances, N_2O emissions are expected to be especially high during periods of incomplete nitrification (incomplete ammonia, NH_3 conversion to either nitrite, NO_2^- or nitrate, NO_3^-) or during periods of high NO_2^- accumulation. Incomplete nitrification is highly likely in plants not specifically designed for nitrification since these plants have a lower target operating solids retention time (SRT) than plants designed for nitrification. Consequently, incomplete nitrification and NO_2^- accumulation is especially promoted Ahn et al. (2009). Yet another factor leading to N_2O emissions from nitrification is the imposition of excess influent TKN loads. Since these loads are not adequately buffered at low operating SRT, the diurnal peaks in influent TKN loading can lead to especially high NH_3 accumulation in such plants. Given that N_2O emissions from nitrification are correlated with the extent of NH_3 accumulation, this is yet another factor exacerbating N_2O emissions from plants not designed and operated for BNR, but where intermittent nitrification can occur (Ahn et al, 2009; Yu et al., 2010).

The emissions from a facility designed to remove nitrogen, the N_2O emissions are expected to be lower than for a cBOD unintentionally performing nitrogen removal. This reduction is primarily because of the higher operating SRT. Owing to the higher target SRT in Levels 1 to 4, the influent TKN loads are better buffered than in the case without BNR. Additionally, the standing NH_3 and NO_2^- concentrations in a system with MLR are also lower than a nitrogen removal facility, which leads to a reduction in nitrification and denitrification associated N_2O emissions. There are two specific strategies for optimizing MLR that could minimize the overall N_2O emissions potential, for a given effluent TN concentration of less than 8 mg-N/L. The first strategy is to achieve near complete nitrification, so as to minimize the standing NH_3 concentrations in the system, which implies that NO_3^- will constitute the majority of the effluent TN load. The second strategy is to minimize the extent of plug-flow in the system, especially in the aerobic zone and thus minimize the NH_3 gradient therein (Ahn et al, 2009; Yu et al., 2010). Given the positive correlation between NH_3 concentrations and N_2O emissions, minimizing plug-flow conditions can also minimize the magnitude of N_2O emissions especially in the upstream regions of the aerobic zone.

It is also conceivable that COD limitation in the anoxic zones can result in N_2O emissions as documented in some studies previously Hanaki et al. (1992). However, through all our intensive monitoring campaigns, N_2O emissions in anoxic zones have been minimal across the board, both in the presence and absence of external COD addition (Ahn et al, 2009). Recent lab-scale results also point to the fact that transient COD limitation contributes minimally to N_2O emissions (Lu and Chandran, 2010).

As more studies are carried out and more data is generated, a greater understanding on the role of feed delivery and configuration has on overall N_2O emissions. Once a level of

confidence is reached with respect to quantifying N₂O emissions, the existing IPCC (2006) approach can be replaced by a more scientific approach.

5.7.8 Methane Emissions

Although largely ignored at WWTPs, methane formation is gaining recognition as a major GHG contributor during sewer system conveyance. The competition of Methanogens and sulfate reducing bacteria (SRB) for substrate is a well-known and documented phenomenon. Given that substrate is not limited in the sewer collection system, both Methanogens and SRB should be able to co-exist and thrive (Robinson and Tiedje, 1984). Thus, it is not surprising that Methanogens thrive in sewer collection systems. Atmospheric scientists point towards domestic sewage as a major anthropogenic methane source (Minami and Takata, 1997).

Methane sewer field measurements coupled with controlled experiments found that hydraulic residence time (HRT) within the sewer collection system and pumping frequency along the sewer system govern methane production (Guisasola et al., 2008; Guisasola et al., 2009). Given the variability in these two operational parameters, HRT and pumping frequency, it is difficult to develop default values for methane production. Rather, a range of values is a more reasonable and valid approach. Their findings suggest that sewer methane emissions range from 20 to 100 mg/L as COD. The emissions indicate that collection system methane could be equivalent to 15-65 percent of the CO₂ equivalents of the electricity used to treat the same amount of wastewater.

These recent revelations by Guisasola et al. (2008; 2009) on the magnitude of methane production in sewer collection systems should prompt future research by funding agencies to better understand formation mechanisms in collection systems. This is especially critical from a GHG emissions perspective as the methane multiplication factor for CO₂ equivalents is 23 (IPCC, 2006).

5.7.9 Point versus Non-Point Pollution

Removing nutrients uses significant energy and chemicals that produce GHG emissions. Reaching exceptionally high levels of nutrient removal results in such high GHG emissions per incremental pound of N and P removed that a point of diminishing returns can be exceeded. Achieving exceptionally high level of nutrient removal is exacerbated by the presence of recalcitrant dissolved organic nitrogen and phosphorus, for which practical removal mechanisms have not been developed. These compounds may not impact water quality significantly in receiving waters. Therefore, removing nitrogen to exceptionally low levels may require removal of virtually all nitrate, nitrite, and ammonia as well as rDON, which can only be done with level 4 treatment. Level 4 treatment also requires removing particulate phosphorus and rDOP.

As previously indicated in this report, non-point sources of nitrogen and phosphorus are significant. A significant reduction in nitrogen and phosphorus might be achievable by using sustainable best management practices that could have considerably less impact on GHG emissions than high levels of treatment at municipalities. A rational and holistic approach to point and non point discharges of N and P could result in a win-win situation: reduced nutrient loads to our waterways with manageable impacts on GHG production.

CHAPTER 6.0 - SUMMARY, FUTURE WORK, AND CONCLUSIONS

6.1 Summary

The wastewater industry has seen increasingly ominous restrictions on nutrient discharges, namely nitrogen and phosphorus. As a result, this report was prepared to provide a bench-top analysis on striking a balance between nutrient removal and sustainability. The objective was to determine if a point of “diminishing returns” is reached where the sustainability impacts of increased levels of nutrient removal outweigh the benefits of better water quality. The measurement used to quantitate the environmental impacts is greenhouse gas (GHG) emissions since it provides a means to normalize data for comparative purposes. Given that sustainability is a broad term, the focus was placed on the following variables while developing the comparative model:

- ☐ GHG emissions
- ☐ Capital costs
- ☐ Operating costs
- ☐ Energy demand
- ☐ Air and water quality
- ☐ Consumables, such as chemicals, gas, diesel, etc.

This study compared five different treatment Levels of nutrient removal as shown in Table 18. With each treatment Level, a mass balance was developed to quantitatively determine the GHG emission equivalents based on the aforementioned parameters.

Table 18. Treatment Level Objectives

Level	Biochemical Oxygen Demand (mg/L)	Total Suspended Solids (mg/L)	Total Nitrogen as Nitrogen (mg/L)	Total Phosphorus as Phosphorus (mg/L)
0	30	30	-	-
1	-	-	8	1
2	-	-	4-8	0.1-0.3
3	-	-	3	<0.1
4	-	-	1	<0.01

The investigation determined that as level of treatment for nutrient removal increased, the impact on sustainability (as measured by green house gas) increased significantly. Achieving treatment Level 4 (N=1 and P<0.02) resulted in a dramatic increase over treatment Level 3 (more than doubling). This raises the question of whether a point of diminishing returns was reached by achieving a small increase in potential water quality that results in a very large impact on the overall environment (as measured by GHGs). For the purpose of consistency, all plants were evaluated at a nominal flow of 10 mgd. Scope 1, 2 and 3 GHG emissions are included with the system inputs.

6.2 Future Work

5. In many regions of the country, non point sources contribute higher nutrient loads than point sources. A rational approach to receiving water nutrient loading such as implementing “best practices” for non point sources may be much more practical than requiring WWTPs to remove nutrients to levels that adversely impact sustainability. Further dialog with regulators on a national and local level is needed to find a regulatory framework that best protects water quality and manages GHG emissions using both non point and point source control
6. Clearly define whether N or P is the limiting nutrient for specific receiving waters.
7. A discussion needs to be initiated with the EPA regarding making N and P limits only on bioavailable N and P; thus taking a portion of rDON and rDOP out of the equation.
8. Initiate research on membranes that discriminate between rDON/rDOP and mono- and divalent ions as a means to overcome brine management issues related to Level 4 (reverse osmosis).

6.3 Conclusions

10. Removing N and P using treatment Levels 3 and 4 may result in negative sustainability impacts that far outweigh the potential improvements to water quality.
11. Removing nutrients results in significant impacts on WWTP sustainability as measured by GHG emissions. For a nominal 10 mgd WWTP, the GHG emissions increased from 1620 CO₂ equivalent metric tons per year for a conventional secondary plant (Level 0 treatment) to 4,450 CO₂ equivalent metric tons per year where nitrogen and phosphorus removal requirements are 3 mg/l N and <0.1mg/l P

- (Level 3 treatment). Further reductions in N and P to 1 mg/l and 0.01 mg/L (Level 4 treatment) increase the GHG emissions to 9,920 CO₂ equivalent metric tons per year.
12. Nutrient removal also increases the capital cost and operating costs of WWTPs. Capital cost increased from \$73 million for a Level 0 facility to \$138 million for a Level 3 facility and \$200 million for a Level 4 facility. Operating costs for a level 0 facility are \$696,000 per year and \$4.3 million per year for a level 4 facility.
 13. The GHG nutrient removal intensity (GHG per incremental pound of N and P removed) increases geometrically as the level of treatment increases. The intensity for moving from level 0 to level 1 is 1.6 for N and 2.9 for P. The intensity for moving from level 3 to level 4 is 26 for N and 504 for P.
 14. Recalcitrant dissolved organic nitrogen, commonly referred to as refractory dissolved organic nitrogen (rDON), impairs municipalities ability to reliably achieve low TN objectives. Effluent limits that require nitrogen values of 2 mg/l or less might require the use of expensive and energy intensive strategies, such as reverse osmosis, that result in monumental GHG emissions.
 15. As with rDON, Recalcitrant dissolved organic phosphorus, commonly referred to as rDOP, hinders a municipalities to meet the total phosphorus value required of Level 4. As a result, an energy intensive technology, such as RO, is required to ensure reliably meeting the treatment objective.
 16. The GHG impacts of all levels of treatment in this document are dominated by energy demand.
 17. Based on the incremental GHG increase per incremental removal, a point of diminishing returns is reached between Level 2 to 3 for both nitrogen and phosphorus removal.
 18. Using reverse osmosis to achieve extremely low levels of nitrogen and phosphorus is impractical due to high costs, significant impacts on GHG, and brine disposal challenges.

CHAPTER 7.0 REFERENCES

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Appendix A – A Detailed Breakdown of GHG Emissions

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Table A- 1. Detailed Breakdown of Greenhouse Gas Emission Results

Treatment	Level 0 No N/P Removal	Level 1 8 mg/L N 1 mg/L P	Level 2 4-8 mg/L N 0.1-0.3 mg/L P	Level 3 3 mg/L N <0.1 mg/L P	Level 4 1 mg/L N <0.01 mg/L P
	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)
Liquid Stream					
Influent Pumping	210	210	210	210	210
Primary Treatment	28	28	28	28	28
Sub-Total Pri.	238	238	238	238	238
Anaerobic Mixing		73	81	79	79
Anoxic Mixing		167	184	178	178
MeOH Act. Sludge			213	213	213
Aeration	1237	1585	1585	1585	1585
MLE Pumping		567	567	567	567
N ₂ O Emissions	7	16	16	16	16
RAS Pumping	142	142	142	142	142
WAS Pumping	85	57	57	57	57
Sub-Total Act. Sludge	1471	2605	2844	2836	2836
MeOH Tert. Denit. Filter				107	107
Filter Pumping		227	227	453	453
Alum (Filtration)			165	422	423
Conventional Filtration (Backwash)		57	57	57	57
Polymer (High Rate Clarifier)				72	72
High Rate Clarifier (Backwash)				40	40
Micro-Filtration (Pumping)					162
Micro-Filtration (Backwash)					40
RO (Transfer Pump)					54
RO (Feed Pump)					2699
RO (Backwash)					40
DM					2483
Disinfection (Hypochlorite)	203	204	203	203	197
Sub-Total Tertiary	203	487	652	1354	6826
Sub-Total Liquid Stream	1913	3331	3735	4428	9900
Solids Treatment					
GBT (Pumping)	57	57	57	57	57

Treatment	Level 0 No N/P Removal	Level 1 8 mg/L N 1 mg/L P	Level 2 4-8 mg/L N 0.1-0.3 mg/L P	Level 3 3 mg/L N <0.1 mg/L P	Level 4 1 mg/L N <0.01 mg/L P
	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)	(CO ₂ eq metric tons/yr)
GBT (Polymer)	1	1	1	1	1
Digester (Mixing)	355	355	355	355	355
Digester (CH ₄)	-986	-713	-775	-702	-703
Centrifuge (Polymer)	2	2	2	2	2
Centrifuge (Energy)	90	77	84	67	67
Fermentation				60	60
Biosolids Hauling	186	165	184	179	180
Sub-Total Solids	-294	-56	-91	19	19
Total	1619	3274	3643	4447	9919

Appendix B – A Detailed Discussion on Nitrous Oxide Emissions at WWTPs

Level 0

Based on ongoing studies at full-scale as part of the Water Environment Research Foundation (WERF) project U4R07, inefficient nitrification and denitrification have been implicated as the main factors leading to N_2O emissions from both BNR and non-BNR processes Ahn et al. (2009). It should be noted that plants designed just for secondary treatment could also potentially nitrify part or all of their influent total Kjeldahl nitrogen (TKN) load at high temperatures (e.g., during summer). Under such circumstances, N_2O emissions are expected to be especially high during periods of incomplete nitrification (incomplete ammonia, NH_3 conversion to either nitrite, NO_2^- or nitrate, NO_3^-) or during periods of high NO_2^- accumulation. Incomplete nitrification is highly likely in plants not specifically designed for nitrification since these plants have a lower target operating solids retention time (SRT) than plants designed for nitrification. Consequently, incomplete nitrification and NO_2^- accumulation is especially promoted Ahn et al. (2009). Yet another factor leading to N_2O emissions from nitrification is the imposition of excess influent TKN loads. Since these loads are not adequately buffered at low operating SRT, the diurnal peaks in influent TKN loading can lead to especially high NH_3 accumulation in such plants. Given that N_2O emissions from nitrification are correlated with the extent of NH_3 accumulation, this is yet another factor exacerbating N_2O emissions from plants not designed and operated for BNR, but where intermittent nitrification can occur (Ahn et al, 2009; Yu et al., 2010).

Level 1

The emissions from an MLE configuration incorporating biological phosphorous removal without chemical addition are expected to be lower than that for just secondary treatment. This reduction is primarily because of the higher operating SRT. Owing to the higher target SRT in Level 1, the influent TKN loads are better buffered than in the case without BNR. Additionally, the standing NH_3 and NO_2^- concentrations in the MLE system are also lower than Level 1, which leads to a reduction in nitrification and denitrification associated N_2O emissions. There are two specific strategies for optimizing the MLE configuration that could minimize the overall N_2O emissions potential, for a given effluent TN concentration of 8 mg-N/L. The first strategy is to achieve near complete nitrification, so as to minimize the standing NH_3 concentrations in the system, which implies that NO_3^- will constitute the majority of the effluent TN load. The second strategy is to minimize the extent of plug-flow in the system, especially in the aerobic zone and thus minimize the NH_3 gradient therein (Ahn et al, 2009; Yu et al., 2010). Given the positive correlation between NH_3 concentrations and N_2O emissions, minimizing plug-flow conditions can also minimize the magnitude of N_2O emissions especially in the upstream regions of the aerobic zone.

It is also conceivable that COD limitation in the anoxic zones can result in N_2O emissions as documented in some studies previously Hanaki et al. (1992). However, through all our intensive monitoring campaigns, N_2O emissions in anoxic zones have been minimal across the board, both in the presence and absence of external COD addition (Ahn et al, 2009). Recent lab-

scale results also point to the fact that transient COD limitation contributes minimally to N₂O emissions (Lu and Chandran, 2010).

Level 2.

Extending the above argument (for Level 1), the magnitude of N₂O emissions with Bardenpho for an even lower effluent TN concentration with methanol addition will be even lower. It is presumed that the lower TN concentrations will be achieved by a mix of higher SRT and external COD addition. The higher SRT will presumably stabilize nitrification, especially in response to diurnal load variations of TKN, leading to lower standing concentrations of NH₃ and NO₂⁻ in the system. Again, N₂O emissions can be minimized for a given effluent TN concentration, by minimizing the effluent NH₃ fraction thereof. Further reductions in N₂O emissions can also be effected by minimizing the plug-flow regime, especially of the primary aerobic zone (Ahn et al, 2009). It should be pointed out that the differences in the N₂O emissions between Level 1 and Level 2 cannot be directly to differences in the configuration (MLE vs Bardenpho) alone, since different levels of TN removal are being achieved in the two configurations. Rather, the different levels of N₂O emissions are due to the different operating SRTs and the correspondingly different nitrogen concentrations and speciation therein. Due to the low magnitude of N₂O emissions from denitrification observed consistently to date, differences in effluent NO₃⁻ concentrations between Level 1 and Level 2 are not expected to contribute significantly to differences in N₂O emissions (Ahn et al, 2009).

Level 3.

N₂O emissions in Level 3 are expected to be similar or minimally lower than for Level 2, if and only if the main difference is in the effluent nitrate concentrations and not in effluent NH₃ concentrations. There is always the danger of overdosing external COD such that heterotrophic growth occurs at the expense of growth of nitrifying bacteria and significant N-removal is by virtue of N-assimilation (Grady et al., 1999). In such a unique scenario, nitrification could be intermittent and unstable (similar to Level 1), resulting in N₂O emissions. However, this unique scenario is expected to be highly unlikely and avoidable given the use of process simulation tools for design and optimization.

Level 4.

Assuming that the only advantage of Level 4 over Level 3 is the removal additional soluble organics, the N₂O emissions in both Levels 3 and 4 are expected to be comparable.

Impact of different levels of EBPR on N₂O emissions

Finally, although there is some evidence on the impact of EBPR on N₂O emissions, the specific mechanisms are related to transient depressions in pH rather than specific EBPR reactions and pathways themselves (Zhou et al., 2008). Thus, the different levels of EBPR are not expected to contribute differentially to N₂O emissions from the different systems considered herein.

Summary

Based on the different levels of BNR treatment and corresponding operating SRTs, N₂O emissions are expected in the following order: Level 0 > Level 1 > Level 2 > (Level 3~Level 4). Higher standing concentrations of NH₃ and NO₂⁻ primarily influence the magnitude of N₂O emissions from the different configurations. Strategies and configurations aimed at minimizing these concentrations (both at steady-state and diurnal transients) will consequently lead to lower

N₂O emissions. The impact of factors such as non-optimal aeration and oxygen intrusion into anoxic zones is not explicitly considered here, since these factors ultimately result in build-up of NH₃, NO₂⁻ among other N-species, which in turn influence N₂O emissions. For a more detailed analysis, the impacts of temperature will also need to be considered in terms of their direct and indirect influence on N₂O emissions. The development of process models to perform a more detailed evaluation of these and additional factors is now underway as part of WERF U4R07.